

DESIGN OF POROUS ASPHALT PAVEMENT FOR STORM WATER MANAGEMENT

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the Degree of*

MASTER OF ENGINEERING

In

INFRASTRUCTURE ENGINEERING

Submitted by

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JULY 2019



DECLARATION

I hereby declare that this work which is being presented in the thesis entitled “**DESIGN OF POROUS ASPHALT PAVEMENT FOR STORM WATER MANAGEMENT**” in partial fulfillment of the requirement for the degree of **Master of Engineering** in the field of **CIVIL ENGINEERING** with specialization in **INFRASTRUCTURE ENGINEERING** at **THAPAR INSTITUTE OF ENGINEERING & TECHNOLOGY (PATIALA)** is an authentic record of my own work carried out during the period from 27.7.2018 to 6.6.2019 under the guidance of Dr. Tanuj Chopra, Sh. Sunil Jain and Sh. Sampath Kumar Pasupunuri.

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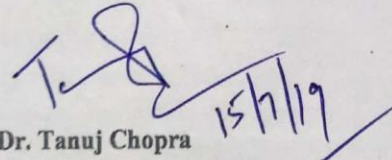
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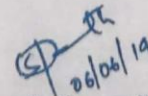

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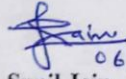
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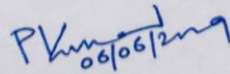
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TABLE OF CONTENTS

DECLARATION.....	Error! Bookmark not defined.
CERTIFICATE.....	ii
ACKNOWLEDGEMENT.....	iii
TABLE OF CONTENTS	iv
LIST OF TABLES.....	ix
LIST OF FIGURES	xi
ABBREVIATIONS	xiv
ABSTRACT	xvi
CHAPTER 1 INTRODUCTION.....	1
1.1 BACKGROUND	1
1.2 PURPOSE OF THIS RESEARCH	1
1.3 OBJECTIVES	2
1.4 SCOPE	2
1.5 PROJECT METHODOLOGY.....	3
1.6 ORGANIZATION OF THESIS.....	5
CHAPTER 2 LITERATURE REVIEW	6
2.1 GENERAL.....	6
2.2 BENEFITS OF POROUS PAVEMENT	10
2.2.1 Improved the Water Quality.....	11
2.2.2 Safety for Driver and Pedestrian	12
2.2.3 Long-Lived Trees	14
2.2.4 Reduction of Noise.....	15

2.2.5 Economic Benefits	16
2.3 ISSUE WITH POROUS PAVEMENT	18
2.3.1 Durability and Strength of Material	18
2.3.2 Freeze and Thaw Cycle	18
2.3.3 Clogging	19
2.3.4 Cost.....	19
2.4 AREAS WHERE POROUS PAVEMENT SHOULD BE AVOIDED	20
2.5 DESIGN OF SURFACE LAYER.....	21
2.5.1 Material	21
2.5.2 Gradation	25
2.5.3 Optimum Asphalt Content.....	25
2.5.4 Performance of Surface Layer.....	26
2.6 FILTER COURSE / CHOKER COURSE.....	28
2.7 RESERVOIR LAYER	29
2.7.1 Gradation.....	31
2.7.2 Hydraulic design	33
2.7.2.1 SCS/ NCRS CN Method	33
2.7.2.2 Outflow Rate and Volume Through Underdrain Pipe.....	35
2.7.2.3 Depth of Reservoir Layer.....	35
2.7.2.4 Permeable Pavement Storage Volume.....	36
2.8 GEOTEXTILE / FILTER LAYER / FILTER BLANKET / OPTIONAL BOTTOM LINER.....	37
2.9 SUBGRADE	39
2.10 OUTCOMES OF POROUS PAVEMENT	39

CHAPTER 3 EXPERIMENT METHODOLOGY.....	42
3.1 SURFACE LAYER	42
3.1.1 Selection of Material	43
3.1.1.1 Aggregates	43
3.1.1.2 Bitumen	45
3.1.1.3 Additives and Fillers.....	46
3.1.2 Selection of Gradation.....	47
3.1.3 Samples Preparation	52
3.1.4 Optimization of Bitumen.....	55
3.1.4.1 Air Void Criteria.....	55
3.1.4.2 Drain-down Test (AASHTO T 305)	60
3.1.4.3 Cantabro Test (Tex-245-F).....	62
3.1.5 Performance Test.....	63
3.1.5.1 Permeability test (FM 5-565)	63
3.1.5.2 Indirect Tensile Strength (D 6931-12).....	67
3.1.5.3 Moisture Induced Sensitivity Test (ASTM D7870/D7870-13).....	68
3.1.5.4 Skid Resistance Measurement.....	69
3.1.5.5 Dynamic Creep Test DD (226:1996).....	70
3.1.5.6 Slab Casting.....	72
3.2 FILTER LAYER GRADATION	78
3.3 RESERVOIR LAYER GRADATION	80
CHAPTER 4 RESULT AND DISCUSSION.....	82
4.1 AGGREGATE TESTING RESULT	82

4.2 BITUMEN TESTING RESULT	83
4.3 STONE-TO-STONE CONTACT CRITERIA.....	83
4.4 AIR VOIDS CONTENT RESULT	85
4.4.1 Maximum Specific Gravity (Gmm)	85
4.4.2 Bulk Specific Gravity (Gmb)	86
4.4.3 VMA and VFA Result.....	89
4.5 DRAIN-DOWN TEST RESULT.....	92
4.6 CANTABRO TEST RESULT	94
4.7 OPTIMUM BITUMEN CONTENT	96
4.8 PERMEABILITY TEST RESULT.....	98
4.9 INDIRECT TENSILE STRENGTH RESULT (IDT)	104
4.10 MOISTURE SUSCEPTIBILITY TEST RESULT	106
4.11 SKID RESISTANCE TEST RESULT	107
4.12 DYNAMIC CREEP TEST RESULT	109
4.13 FILTER LAYER.....	110
4.13.1 Filter layer VCA_{DRC}	110
4.14 RESERVOIR LAYER.....	111
4.14.1 Reservoir layer VCA_{DRC}	111
4.14.2 Reservoir Layer Hydraulic Design.....	112
4.15 DEMONSTRATION OF PROTOTYPE.....	114
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS	117
5.1 CONCLUSION.....	117
5.2 RECOMMENDATION	118

REFERENCES 119

LIST OF TABLES

Table 2. 1 : Pollution Removal Efficiencies	11
Table 2. 2 : Category of Porous Pavement	20
Table 2. 3 : Various Gradations for the Design of Surface Layer of Porous Asphalt Pavement.....	25
Table 2. 4: Gradation for Filter Layer AASHTO NO. 57	29
Table 2. 5 : Reservoir Layer Gradation AASHTO NO. 3	31
Table 2. 6 : Reservoir Layer Gradation AASHTO NO. 2	31
Table 2. 7 : Group of Soil for Hydraulic Design	34
Table 2. 8 : Runoff Curve Number for SCS Method.....	34
Table 2. 9 : Layer Coefficients	37
Table 2. 10 : Properties of Non-Woven Geo-textile Fiber	38
Table 3. 1: ASTM Gradation.....	49
Table 3. 2 : NCAT 2000 Gradation	50
Table 3. 3: UNHC & NAPA Gradation.....	51
Table 3. 4 : Material Used for Casting of Slab.....	72
Table 3. 5 : Selected Gradation for Filter Layer	78
Table 3. 6 : Selected Gradation for Reservoir Layer	80
Table 4. 1 : Physical Property of Aggregates	82
Table 4. 2 : Bitumen Properties as Observed in the Laboratory.....	83
Table 4. 3 : Void in Coarse Aggregate Mix for Surface Layer	84

Table 4. 4 : VCA(Dry Rodded Condition) for Surafce Layer	84
Table 4. 5 : Gmm by Rice Apparatus	85
Table 4. 6 : Maximum Specific Gravity (Gmm) by the Back Calculation.....	86
Table 4. 7 : Bulk Specific Gravity (Gmb) by Core Lok Apparatus.....	87
Table 4. 8 : Bitumen Content v/s Air void content.....	88
Table 4. 9 : VMA AND VFA	91
Table 4. 10 : Summary of VMA and VFA	92
Table 4. 11 : Draindown Test Result.....	93
Table 4. 12 : Cantabro Test Result on Dry Specimen	94
Table 4. 13 : Cantabro Test Result on Wet Specimen.....	95
Table 4. 14 : Summary of All the Test Results to Decide Optimum Binder Content	97
Table 4. 15 : Permeability Test Result at Bitumen Content 5%	100
Table 4. 16 : Permeability Test Result at Bitumen Content 5.5%	101
Table 4. 17 : Permeability Test Result at Bitumen Content 6%	102
Table 4. 18 : Summary of Permeability Test Result at Three Bitumen Content	103
Table 4. 19 : Indirect Tensile Strength (ITS) Result on Dry Condition	104
Table 4. 20 : Indirect Tensile Strength (ITS) Result on Wet Condition.....	105
Table 4. 21 : Moisture Induced Susceptibility Test Result.....	106
Table 4. 22 : Skid Resistance of Permeable Aspahl Pavement and Dense Aspahl Pavement on Dry and Wet Condition.....	108
Table 4. 23 : Dynamic Creep Test Result.....	109
Table 4. 24 : Filter Layer VCA (Dry Rodded Condition)	111
Table 4. 25 : Reservoir Layer VCA (Dry Rodded Condition)	111
Table 4. 26 : Prameters Adopted in Hydraulic Design.....	113

LIST OF FIGURES

Figure 1. 1 : Flow Diagram for Sequence of Activities.....	3
Figure 2. 1: Different Types of Porous Pavements.....	7
Figure 2. 2 : Porous Bitumen Pavement Structure	9
Figure 2. 3 : A Close up View of Porous Bitumen Pavement	9
Figure 2. 4 : Porous Asphalt Pavement on Left and Conventional Pavement on Right Separated by Cement Concrete Wall.....	10
Figure 2. 5 : Two Model (a) and (b) Consisting of Three and Four Layers of Porous Asphalt Pavement.....	12
Figure 2. 6 : Friction Coefficient of Porous and Dense Pavement During Dry and Wet Conditions.....	13
Figure 2. 7 : Water Penetration form Porous Pavement(left) and Dense Pavement(right) ...	13
Figure 2. 8 : A Dead Tree Planted in Densely Paved Park.....	14
Figure 2. 9 : Heavily Used Area with Porous Bituminous Pavement	15
Figure 2. 10 : Noise Level for Different Types of Pavements.....	16
Figure 2. 11 : Permeable Bitumen Parking Area Protecting Stream Water Quality	17
Figure 2. 12 : Typical Cross Section of Permeable Bitumen Pavement.....	21
Figure 2. 13 : Typical View of Laying and Compaction of Porous Pavement.....	23
Figure 2. 14 : Roof Rainwater Harvesting Adjusted with Permeable Bitumen Pavement....	30
Figure 2. 15 : Close View of Extension of Reservoir Course for Overflow	32
Figure 2. 16 : Emergency Flow in Porous Asphalt Pavement	32
Figure 2. 17 : Minimum Recommended Compacted Permeable Bitumen Pavement Thickness	37

Figure 2. 18 : Shows the View Just After Rain	40
Figure 2. 19 : Shows the View During Rain.....	41
Figure 3. 1 : Methodology for Surface Layer Design.....	43
Figure 3. 2 : Close View of Aggregates Used Under Present Research Work.....	45
Figure 3. 3 : Pellet Fiber	46
Figure 3. 4 : Selection of Gradation.....	47
Figure 3. 5 : Selected Gradation v/s ASTM Gradation	49
Figure 3. 6 : Selected Gradation v/s NCAT 2000 Gradation.....	50
Figure 3. 7 : Selected Gradation v/s UNHC & NAPA Gradation	51
Figure 3. 8 : Flow Process of Making Marshall Samples.....	52
Figure 3. 9 : Mixing and Compaction Temperature Graph	53
Figure 3. 10 : Methodology for Selection of Optimum Binder Content	54
Figure 3. 11 : Design Criteria for Optimization of Bitumen Content in Permeable Bitumen Mix.....	55
Figure 3. 12 : Rice Apparatus	57
Figure 3. 13 : Separated Aggregates	57
Figure 3. 14 : Flow Process of Core-Lok Test.....	59
Figure 3. 15 : Drain-down Basket.....	61
Figure 3. 16 : Loss Angles Abrasion Machine	63
Figure 3. 17 : Apparatus for Permeability Test	65
Figure 3. 18 : Permeability Test Setup	66
Figure 3. 19 : Indirect Tensile Strength Machine	67
Figure 3. 20 : MIST Machine	68

Figure 3. 21 : British Pendulum Tester.....	69
Figure 3. 22 : Input Parameter Screen	70
Figure 3. 23 : Complete Setup of Dynamic Creep Test.....	71
Figure 3. 24 : Failed Sample.....	71
Figure 3. 25 : Inside View of Slab Casting Machine.....	73
Figure 3. 26 : Front View of Slab Casting Machine.....	74
Figure 3. 27 : Prepared Slab	75
Figure 3. 28 : Core Cutting Machine	76
Figure 3. 29 : Front View of Saw Cutter	77
Figure 3. 30 : Side View of Saw Cutte	77
Figure 3. 31 : Selected Gradation for Choker Course	79
Figure 3. 32 : Selected Gradation for Reservoir Layer.....	81
Figure 4. 1 : Asphalt Content v/s Air Void.....	89
Figure 4. 2 : Bitumen Content Versus Draindown Value.....	94
Figure 4. 3 : Bitumen Content Versus Cantabro Loss on Dry Specimen	95
Figure 4. 4 : Bitumen Content Versus Cantabro Loss on Wet Specimen.....	96
Figure 4. 5 : Binder Content V/S Permeability.....	103
Figure 4. 6 : Bitumen Content Versus Moisture Susceptibility.....	107
Figure 4. 7 : Skid Resistance of Permeable Aspahlrt Pavement and Dense Aspahlrt Pavement on Dry and Wet Condition.....	108
Figure 4. 8 : Bitumen Content versus Permanent Strain	110
Figure 4. 9 : Prototype for Porous Asphalt Pavement	115
Figure 4. 10 : Prototype Showing Layers in Porous Asphalt Pavement.....	116

ABBREVIATIONS

- AASHTO American Association of State Highway Transportation Official
- ASTM American Standard of Testing and Material
- BMP Best management practice
- CL Cantabro loss
- CN Curve Number
- D_p Depth of Reservoir
- DRY Dry Rodded Condition
- FHWA Federal Highway Administration
- G_b Specific Gravity of Binder
- G_{mb} Bulk Specific Gravity of Compacted Mix
- G_{mm} Maximum Specific Gravity Loose Mix Aggregates
- G_{se} Effective Specific Gravity of Mix
- HMA Hot Mix Asphalt
- IDT Indirect Tensile Strength
- IDT Indirect Tensile Strength
- k Coefficient of the Permeability
- MIST Moisture Induced Sensitivity Test
- *MIST* Moisture Induced Sensitivity Test
- MORTH Ministry of Roads Transportation Highway
- NAPA National Asphalt Pavement Association
- NCAT National Centre of Asphalt Technology
- OGFC Open Graded Friction Course
- P_b Percentage of the Binder by Total Mix Weight
- P_{ca} Percentage of Coarse Aggregates in the Mix
- P_s Percentage of Aggregate by the Total Mix of Aggregate

- SN Skid Number
- TSR Tensile Strength Ratio
- UNHC University of New Hampshire Stormwater Center
- V_a Air Void Content
- VCA Void in Coarse Aggregate
- VFA Voids Filled with Asphalt
- VG Viscosity Grade
- VMA Voids in the Mineral Aggregate
- γ_s Unit Weight of Coarse Aggregates
- γ_w Unit Weight of Water
- μ Coefficient of Friction

ABSTRACT

Water is most important substance on earth for sustaining life. At present, one third of the world population is facing water scarcity and the situation is going to worsen in the future. At present depletion rate, it is estimated that this number can grow upto two third of the world population in the coming future, unless we come up with the some indigeneous water conservation techniques and technologies. One such technology is porous asphalt pavement, which can help in achieving effective strong water management.

The design of the porous asphalt pavement differ from the regular pavement. The Porous Asphalt Pavement has porous structure which allows water to percolate through the pavement into the soil, thus recharging the ground water table. Asphalt Pavement has many advantages like reducing the amount of surface runoff, noise reduction, skid improvement on the surface of the pavement and improving surface reflectivity etc, so this technology can not only help in water conservation but can also be beneficial in improving the performance and safety characteristics of the road. The important feature which enables the asphalt pavement to exhibit a porous nature is the increase air void content. Air void content of the asphalt mix is the key parameter which determines the design and performance of the porous asphalt pavement. The objective of this study is to come up with an effective design for three layers of porous asphalt pavement named as viz. surface layer, filter layer / choker layer and reservoir layer. Surface layer is designed using Marshall Mix design methodology, considering Indian climatic condition. Performance testing including drain-down susceptibility, cantabro susceptibility, moisture induced damage susceptibility, indirect tensile strength testing, dynamic creep testing, skid measurement and permeability testing will be conducted in this study to design porous asphalt pavement.

CHAPTER 1 INTRODUCTION

Chapter 1st gives an idea of porous asphalt pavement, their purpose, objective & scope of porous asphalt pavement.

1.1 BACKGROUND

There are three types of pavement viz., flexible pavement which includes bituminous pavement, rigid pavement which includes cement concrete pavement and the third one is interlocking concrete paver block pavement. All these three types of pavement are mostly constructed as dense pavements for roadways and the parking lots. All three categories of the pavements when constructed using open graded mixes are known as porous pavement. The porous pavements were first developed in United States and now well established. Full depth permeable bitumen pavement is used in parking lots and full depth permeable bitumen roads are very general in United State and Europe. Porous pavements technology is in very high demand for light traffic roads and parking areas as an alternative practice for Storm water management. The porous pavement actually used for water harvesting purpose because this pavement allows water to pass through pavement structure.

1.2 PURPOSE OF THIS RESEARCH

Purpose of this dissertation work is to develop specification for flexible porous pavements which may be executed for storm water management under Indian climatic conditions. The outcome of this research project will give guidelines to the policy makers, engineers and the contractors to construct the porous asphalt pavement for groundwater recharge and storm water management. The idea behind this concept is to conserve the water bodies and to make a balance for the water cycle and further improve the water quality through natural filtration process. The water table in many states like Haryana, Punjab, Gujarat, Bihar and Delhi is decreasing at a very high rate. All types of construction, parking lots and light trafficked road and sidewalk etc. should be designed by the town planners, various state agencies and engineers in such a way that developed structures have suitable means for water harvesting. The government should make compulsory use of porous asphalt pavement in parking lots and low traffic area so that it will recharge the ground water.

1.3 OBJECTIVES

Objective of study are as under:

- i. To design the porous asphalt layers, which consist three layers (surface course, choker course, and reservoir course).
- ii. To optimize the binder content by Marshall mix design method for porous asphalt pavement.
- iii. To develop standards for porous asphalt pavement according to Indian condition.

1.4 SCOPE

The pavement construction materials viz. aggregate, asphalt, and additives to be selected first. The Aggregate impact test (IS- 2386 part IV or ASTM C131), Los Angeles abrasion test (IS: 2386 part-4) or ASTM C131), specific gravity and water absorption test (as per IS: 2386 part 3), shape test (IS: 2386-I) and stripping value test (IS: 6241-1971). The grade of asphalt will be selected on the basis of environment, traffic and expected open graded friction course performance. The various test conducted on the bitumen samples under this project are penetration test (IS: 1203-1978), ductility test IS: 1208-1978, viscosity test (IS: 1206-1978 or ASTM D4402/D4402M-15) and test for softening point (IS: 1205-1978).The optimum grading will be selected according to the different test methods to ensure stone on stone contact as per ASTM C29/C29M. The optimum bitumen content selection was done on the basis of air voids (AASHTO T209)/(AASHTO T331), drain-down test result (AASHTO T 305) and particle loss resistance test with consideration of the dry and wet specimen(Tex- 245-F). Performance of designed mix will be evaluated for rutting resistance, permeability (FM 5-565), indirect tensile strength (D 6931-12), moisture susceptibility (ASTM D7880/D7870-13), skid resistance(ASTM E303) and dynamic creep (DD 226:1996). The choker/filter and reservoir courses were designed on the basis of the air void criteria.

1.5 PROJECT METHODOLOGY

First of all aggregate and bitumen will be selected and tested to meet the specified requirements. After testing the bitumen and the aggregate, the mix design will be carried out on the basis of the selected gradation to meet the optimum binder criteria. After selecting the optimum binder performance test will be conducted. After designing surface layer next step is to design filter and reservoir layer. Under this study it is also planned to demonstrate water harvesting system prototype in the laboratory by using the designed porous asphalt pavement. The flow diagram for sequence of activities adopted during the laboratory study is shown in Figure 1.1. The detailed methodology carried for this study is shown in Table 1.1

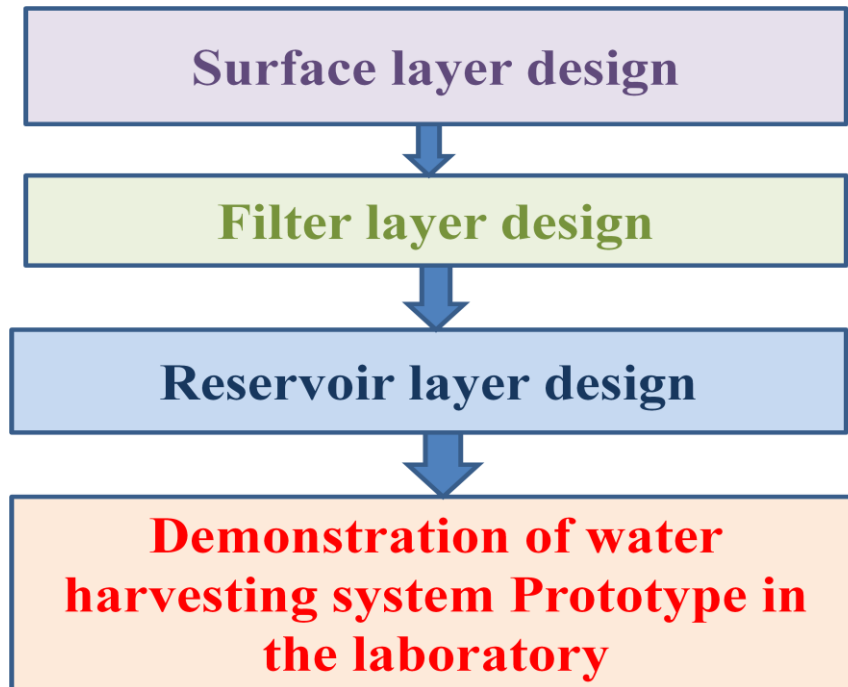
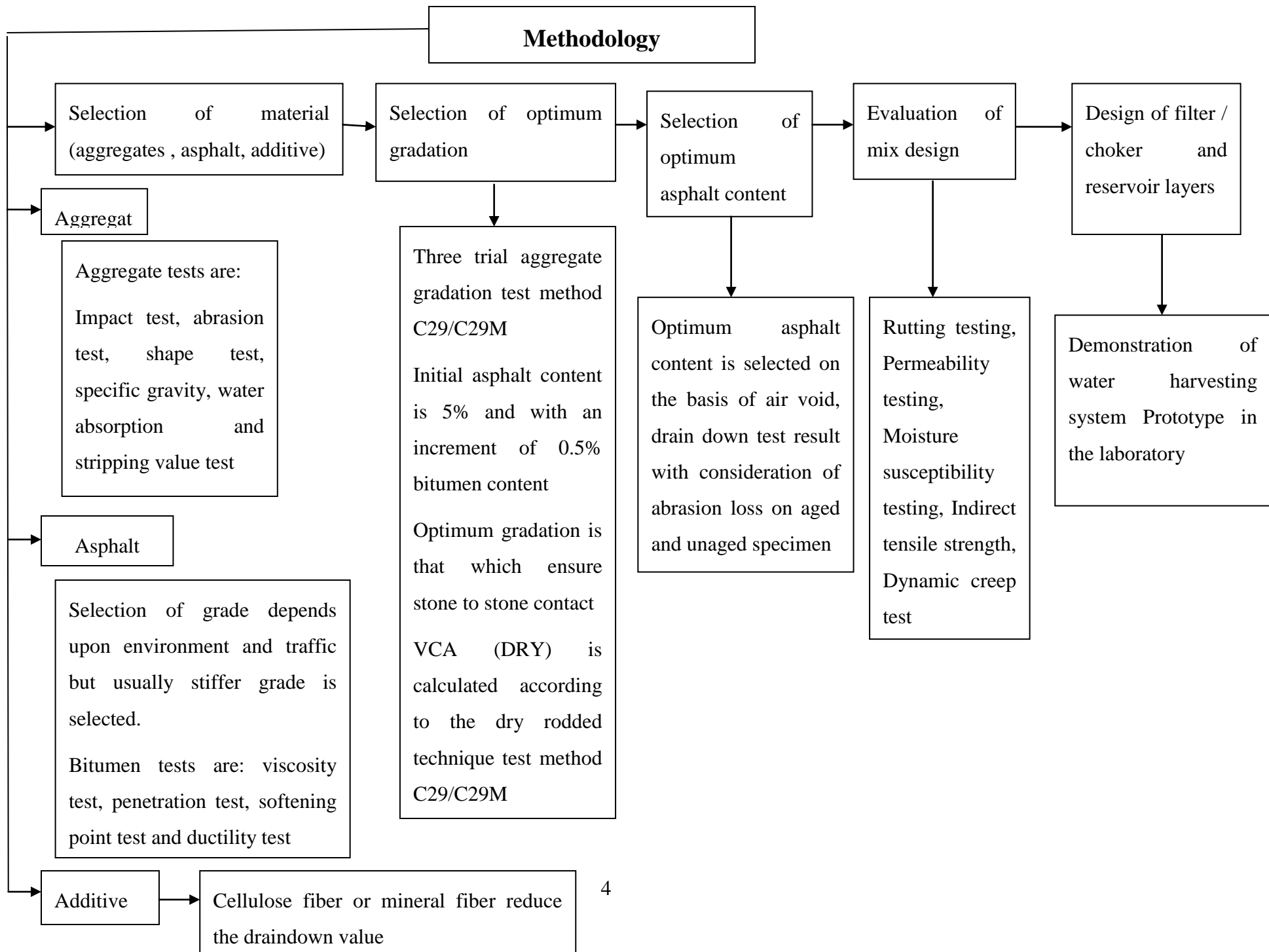


Figure 1. 1 : Flow Diagram for Sequence of Activities



1.6 ORGANIZATION OF THESIS

Chapter 1st gives a general idea of background, scope and objective of the dissertation work.

Chapter 2nd gives literature review on permeable asphalt pavement.

Chapter 3rd explains the experimental study used for design of surface layer, filter layer and reservoir layer consider under the scope of work.

Chapter 4th describes result and discussion for all three layers of porous asphalt pavement.

Chapter 5th gives conclusion and future recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 GENERAL

Ground water table of India is decreasing at very fast rate. The main reason of ground water table depletion is unnecessary unplanned use of ground water and decreased rate of recharging the ground water. So question arise how ground water level will be improved? Ground water level will be improved by percolating rain water into the ground, but rain water instead of recharging it evaporates more due to urbanization. According to the research the 400 million hectare meter rain water comes on earth and 470 million hectare meter water evaporated.

The urbanization is increasing day by day and the urban drainage system is overloaded. The redesigning or improvement of present drainage is very gigantic task that requires lot of time and money. Hence, urbanization should be in a systematic manner so that it does not create problem for present as well as for the future generation. Urban development should be in such a manner that it reduce the runoff by infiltration, storing or by any other ways. The idea behind this concept is to conserve the water bodies, to make balance in water cycle and improve the water quality and this is known as storm water Best Management. So BMP can be achieved through permeable pavement [Marchioni et al. 2015].

The planners of a city, architects and civil engineers should implement water harvesting technology and water management in design of all types of construction, parking areas and low volume roads/streets. The permeable bitumen pavements which can be used for a parking area or light traffic roads/streets are good solution to harvest rainwater, storm water management and recharge the ground water table [Kandhal et al. 2014].

As compared to the ordinary pavement the permeable bitumen pavement is constructed to percolate water through its layers. Since, porous pavement percolate water through pavement structure, it means such pavement has more voids and in pavement design estimation of air voids content are critical. Further, the maintenance of porous asphalt pavement are very difficult. The porous asphalt pavement have limited application specially it may be used for light trafficked area and parking area etc. So if water will percolate from

the layer then design of porous pavement will be critical, maintenance will also be difficult and application will also be limited.

Porous pavement will be of three type's viz. permeable bitumen pavements, permeable concrete pavements and porous concrete paver pavements [Abustan et al. 2012].

Permeable bitumen pavement: The permeable bitumen pavement is same as conventional pavement (HMA) but it contains less fine particles as compared to ordinary pavement. Compaction in permeable bitumen is also very less as compared to ordinary pavement.

Permeable concrete pavement: Porous concrete pavement contains cement, water and any admixtures.

Permeable interlocking concrete blocks: Permeable precast pavers can also be used as water harvesting technique. These contain small holes and special construction material for supporting vehicles. [Weiss at all. 2019].

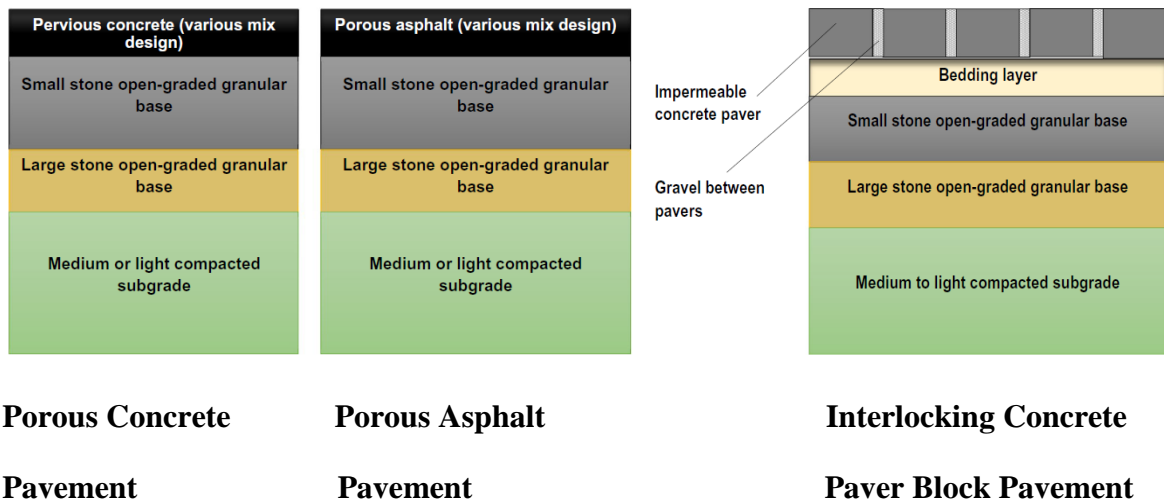


Figure 2. 1: Different Types of Porous Pavements

The selection of type of pavement to be used will depend on the condition of the site and requirements of the project. In this research work, only porous asphalt pavement will be deal and discussed. The porous pavement has many benefits like skid reduction of the

pavement, reduce spray and splash behind the vehicle, improve surface reflectivity, noise reduction, ground water recharge and water management etc. These pavements are mostly constructed for the low volume roads like parking, sidewalks etc but depending upon purpose of providing these porous pavements may also be constructed for highways.

The design of the layers of the porous asphalt pavement varies from country to country. In united state most of agencies generally used NCAT 2000 design method [Setyawan et al. 2017, Lebens at al. 2012]. The porous asphalt pavement has three layer structure viz. surface layer, filter layer/choker course and the reservoir layer. The surface course consists of 50mm to 100mm thick layer of open graded asphalt mix. The filter course consists of 25mm -50mm of crushed stone and provides a suitable platform for surface layer. The reservoir layer consists of 40mm-80mm mix layer for storing water.

- Surface layer: Surface layer transfer the load from the vehicle to filter course and has high void content varying from 18% to 22% or more, which allow water to pass directly to the base subgrade [Schaus 2007].
- Filter course: Filter course or the choker course provide stable platform for the surface layer and prevent the migration of the surface particle from surface layer and to the reservoir layer.
- Reservoir layer: The base material which is reservoir layer should placed on the uncompacted subgarde and consist of clean, uniformly graded aggregates for storing water during heavy rain. The depth of the reservoir layer according to New Jersey Stormwater Best Management, depend on rainfall intensity, gradation of broken stone that is void content (finer aggregate should be less to obtain higher permeability) and the permeability of soil. Pneumatic roller not to be used for compaction of porous pavement because their action decreases the permeability of the pavement by closing the voids of the pavement [Lebens et al. 2012].

All these features of porous pavement are very attractive but still requires some modification in the design because porous pavement cannot long lasting due to clogging of voids, maintenance is very difficult, cannot carry heavy traffic, durability is very less and anaerobic condition may be developed in reservoir layer if water is stagnated for more times

etc. All the characteristics of each layer i.e type of material used, gradation of each layer, type of test and their performance will be discussed below in detail. Figure 2.2 shows a typical porous bitumen pavement structure [Schaus 2007] and figure 2.3 shows a close view of porous bitumen pavement [Kandhal et al. 2014]

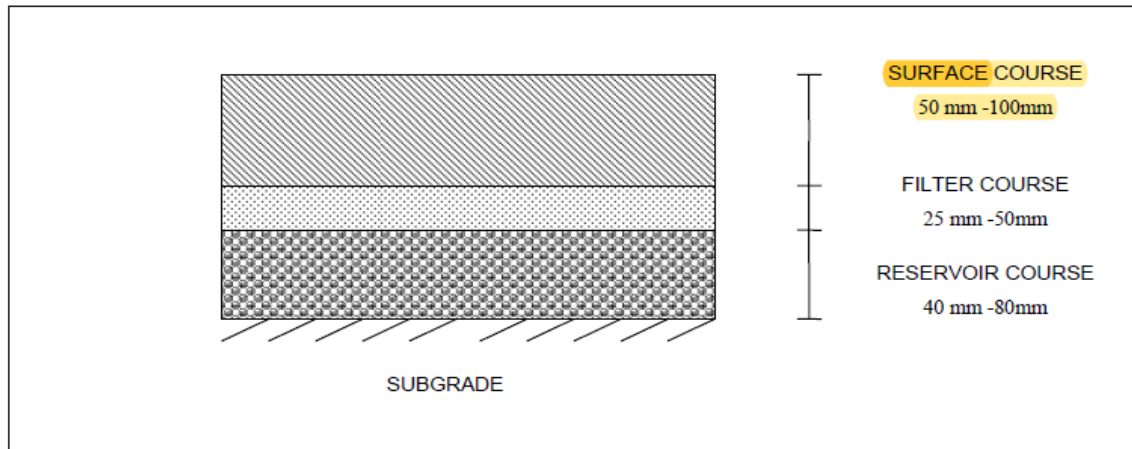


Figure 2. 2 : Porous Bitumen Pavement Structure



Figure 2. 3 : A Close up View of Porous Bitumen Pavement

General structure of the porous pavement is shown in Figure 2.4 on the left side and the conventional pavement on the right side [Kandhal et al. 2014].

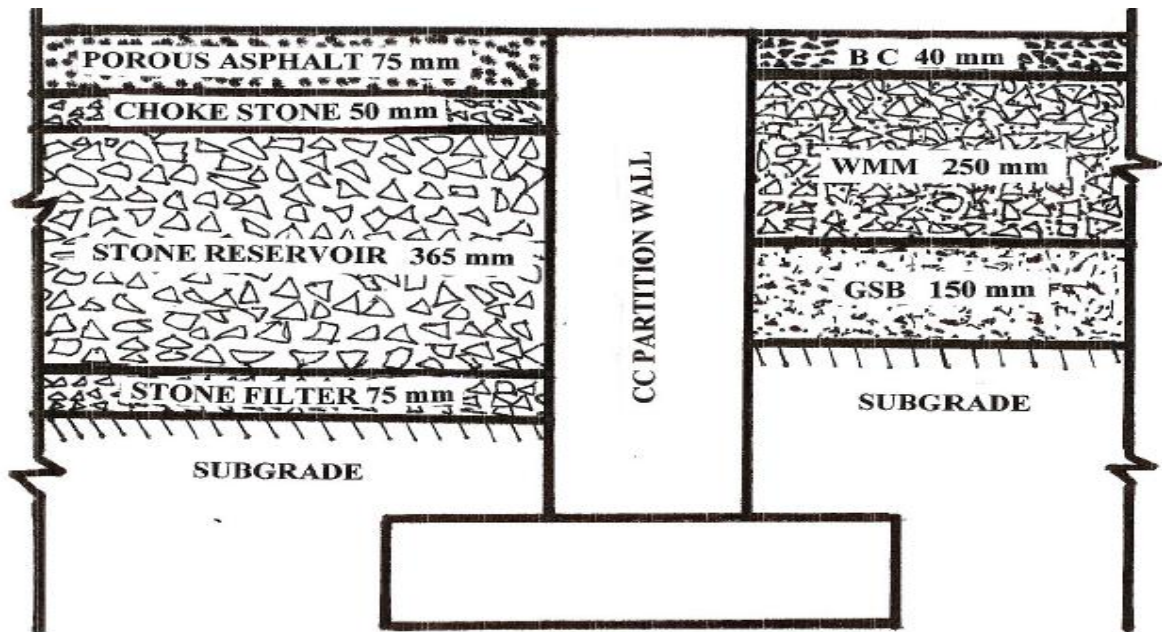


Figure 2. 4 : Porous Asphalt Pavement on Left and Conventional Pavement on Right Separated by Cement Concrete Wall

2.2 BENEFITS OF POROUS PAVEMENT

Porous pavement provides not only the environmental benefits but also the safety benefits. Porous pavement provides storm water Best Management Practice (BMP) by reducing the splay and spray given by tire of vehicle which increases the visibility on the surface, reducing the noise level, fuel consumption and increasing the safety of the driver and pedestrian. People leaving in nearby place to porous pavement have no problem of epidemic disease [Mallick et al. 2000, Alvarez et al. 2006]. Permeable pavements increase road safety in heavy storm water and slippery area [Setyawan et al. 2017, FHWA 2015, Holleran et al. 2016]. According to **NAPA** the permeable pavement with respect to storm water management, it may increase the permeability of subgrade, improve water quality by filtering it from the layers of porous asphalt pavement and this filtered water can be collected according to the need of the site without any additional requirement of costly water treatment process. Some benefits of porous pavement are summarize below.

2.2.1 Improved the Water Quality

Road surface get polluted either directly from source or from vehicle on the road. From vehicle the pollutants released are polycyclic aromatic hydrocarbon (PAH), heavy metals, suspended particle and oil and grease. Wearing of tires, corrosion of metal cause zinc and cadmium pollution and burning of fossil fuel cause nitrate and nitrite pollution. Porous pavement provides the efficient system to reduce the pollutants in ground water. It removes total suspended solid (TSS), metals and oil & grease [FHWA 2015, Holleran et al. 2016, NAPA IS 131]. It was observed that phosphorous removal is limited and nitrogen and chloride removal is negligible, but it reduce the quantity of salt needed in winter during ice formation, it needed only 0 to 25% of salt. Average concentration of nitrogen, zinc in dissolved form, nitrate, nitrite and chemical oxygen demand showed a little change but runoff from the permeable roads has good quality than the conventional pavement [FHWA 2015, NAPA IS 131]. Table 2.1 shows pollution removal efficiencies for various impurities [NAPA IS 131].

Table 2. 1 : Pollution Removal Efficiencies

Layer	Removal of Suspended solids in %	Phosphorous (% removal)	Zinc Removal in %	Hydrocarbons Removal in %
Porous pavement	99	38	96	99

Two models of porous asphalt pavement consisting of three layers and four layers were prepared as shown in Figure 2.5(a) & Figure 2.5(b) respectively. Characteristics such as ph, copper, zinc, phosphorus, chromium, dissolved oxygen, nitrite and iron was measured. The two models collect water, one directly from sky and one from street storm water runoff. Measurements were performed only when the height of water into the sample is greater than 5mm. The amount of storm water collected in each sample is approximately 20litre and first 15minute of rainfall was discarded because it may contain debris and may clog the void of layer. Observation was made that the concentrations of total phosphorus in

storm water collected from street is more than the rainwater collected directly from sky. It was concluded permeable bitumen pavement was able to filter some pollutants and also suggested that permeable bitumen pavement must be avoided in proximity to the sources such as sewers, polluted rivers and landfills [Padilha Thives et al. 2014].



Figure 2. 5 : Two Model (a) and (b) Consisting of Three and Four Layers of Porous Asphalt Pavement

2.2.2 Safety for Driver and Pedestrian

Porous pavement and dense pavement have same friction during dry condition, but during wet condition water layer may formed on dense surface and cause slipping of wheel of vehicles [Ferguson 2005]. Porous pavement due to OGFC (OGFC has void content 18% to 25%) can pass water from its surface and improve safety on wet surface for the pedestrian and the drivers. More voids content improve the safety for driver and pedestrian by preventing, skidding of wheel of vehicles on wet surface, removing the phenomena of spray and splay behind the vehicle. Spray occur with fine particle on wet surface and splay occur with coarser particle on wet surface, both these create poor visibility on surface. Thus porous asphalt pavement increases visibility by decreasing the reflection of light to the eye of driver from the surface of road [Alvarez et al. 2006]. At night due to excellent draining property these pavement produce little glare from the light of vehicles. The porous asphalt pavement does not need hydroplaning like side by drainage, chamber etc. On other hand

dense pavement do not allow water to percolate through the layers and thus dense pavement has all above mentioned difficulties and also needs hydroplaning. Figure 2.6 shows comparison of friction between permeable asphalt pavement and dense pavement. Figure 2.7 shows Water from tank penetrating into pavement on left side (porous pavement) and water from tank moving on right side (dense bitumen pavement) [Kandhal et al. 2014].

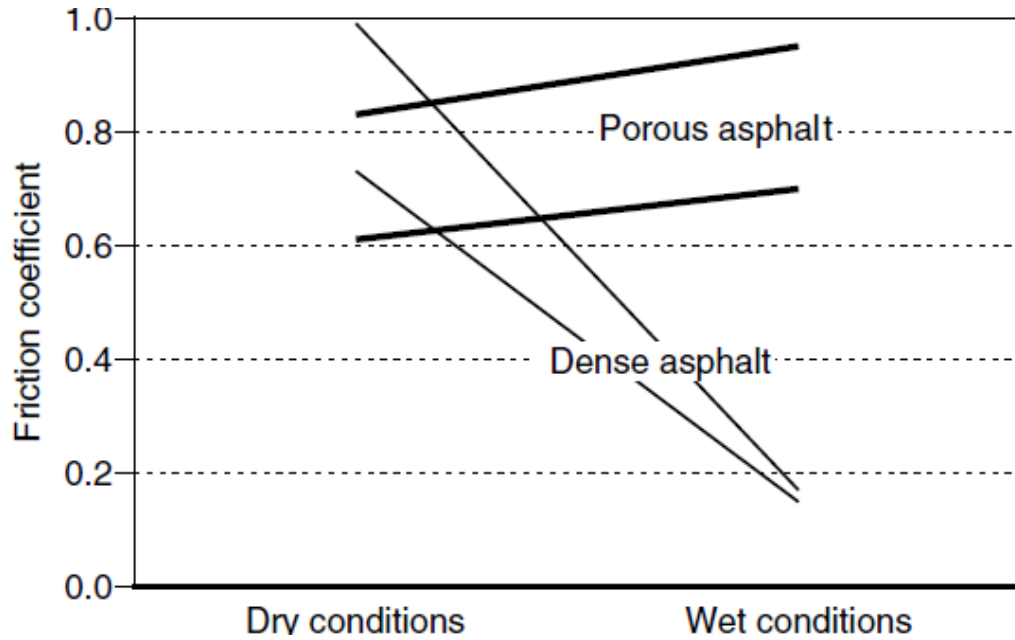


Figure 2. 6 : Friction Coefficient of Porous and Dense Pavement During Dry and Wet Conditions



Figure 2. 7 : Water Penetration form Porous Pavement(left) and Dense Pavement(right)

2.2.3 Long-Lived Trees

Every year trees are planted to make the atmosphere clean and consider as environment purifier. Trees replace carbon dioxide into oxygen and purify air quality by reducing sulphur dioxide, carbon monoxide and other gaseous etc. Trees cool the air, provide house for birds and animals, absorb noise and reduce glare. Their arrangement provides a view of architecture, a point of attraction, increase workability and add economic to our country. All these benefits from the trees can be taken if it grows to its full growth. Trees, which could live more than 100 years or more, when planted near dense pavement, could live only seven year after planting. For the full growth of tree, root zone required is 24 to 36 inches with availability of water, nutrients and free air. Trees which are planted in a pit cannot grow full because of limited root zone depth and insufficient supply of nutrients. Tree dies in very small time shown by Figure 2.8 given below [Ferguson 2005].



Figure 2. 8 : A Dead Tree Planted in Densely Paved Park

A porous pavement may provide all sufficient nutrients because it allows water to percolate and exchange of oxygen with root zone. This indicates the porous asphalt pavement provides healthy soil structure to the plant for its full growth. Figure 2.9 shows a park paved with porous bitumen pavement in New York. The upper layer is permeable and beneath there is a mixture of structural soil and aggregates providing a root area for trees and advantageous for thousands of pedestrians per day [Ferguson 2005].



Figure 2. 9 : Heavily Used Area with Porous Bituminous Pavement

2.2.4 Reduction of Noise

Traffic noise is a problem for the adjoining area near busy roads and urban streets. Noise on roads generates from engine, rolling tires and rough surface roads. The unit of intensity of sound energy is bel (B) and one tenth of bel (B) is equal to one decibel (dB). One decibel is the amount of sound energy detectable by human ears. Human ears can tolerate up to 120 to 140 dB without any pain. So noise reduction is a challenging factor in highways and it can be reduced by the construction of masonry walls. These walls can reduce noise 10dB to 15dB. But these require funds, space and are feasible only in some stretches [Ferguson 2005]. Porous pavement provides an effective method to reduce noise levels. Many countries have

adopted porous pavement for the purpose of noise reduction. Mostly European countries have adopted the porous pavement as noise reduction pavement and united state adopted as safety improvement on wet surface. 3 to 6 dB noise level reduction was noted in permeable pavement from the ordinary pavement [Kandhal et al. 2014]. High comfort is observe for driver since the noise level in vehicle and outside the vehicle is very less. Noise level for different type of pavements is shown Figure 2.10 and lowest noise level is observed in OGFC.

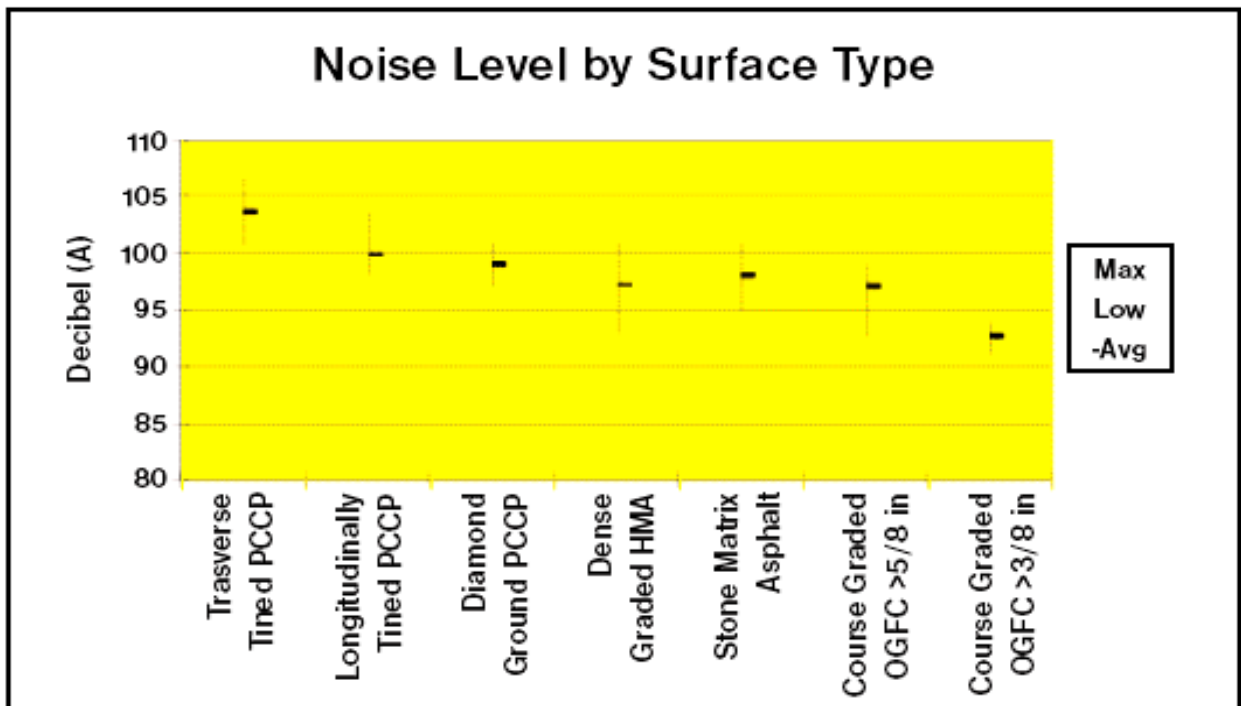


Figure 2. 10 : Noise Level for Different Types of Pavements

2.2.5 Economic Benefits

Use of porous road in place of dense road has reduced cost of construction. Use of porous pavement provides storm water function and eliminates costly pipe and drainage system. Figure 2.11 shows the permeable bitumen parking area of shopping centre protecting the stream water quality, stream is flowing in the background behind the curb. Porous pavement did not need any additional land for storm water management and in case

of dense pavement parking lot require additional land for storm water management [Ferguson 2005].

Additionally porous pavement may have more cost of stone bed but this cost is generally cover by drainage pipes and inlets. Porous pavement does not require more earthwork and less deep excavation and best economical choice when consider by eliminating detention basin [NAPA IS 131]. Economic benefit of porous pavement was also observed in fuel consumption as it saves 2% fuel as compared to conventional pavement. Wear and tear of tire also reduces by decreasing the stress on tire. The reduction in hydroplaning reduce the accident , reduction in noise level beneficial for the driver and the pedestrian, improving water level of ground and implementing the best management practice all these advantages can be converted into the term of economic value and prove that porous asphalt pavement are economical as compared to dense asphalt pavement [Alvarez et al. 2006].



Figure 2. 11 : Permeable Bitumen Parking Area Protecting Stream Water Quality

2.3 ISSUE WITH POROUS PAVEMENT

2.3.1 Durability and Strength of Material

As porous pavement is open graded it provides less structural contribution than the dense pavement. The durability and strength of the permeable bitumen pavement is less in comparison to the conventional bitumen pavement. Performance of pavement reduces in term of durability and functionality.

Durability is experienced with raveling which ones start then progressively increases. Improvement in binder, admixture and gradation has been done to increase the durability. According to the survey by NCAT a service life of 8 years of porous pavement was reported in 1998.

Functionality reduces in term of permeability and noise absorption. Permeability and noise absorption are the parameters of air voids, when these get clogged functionality get reduce.

Other factor which affects durability and strength of permeable bitumen pavement are stripping and raveling. Stripping is debonding of aggregates and asphalt when water comes in contact with layer. Raveling or rutting is loss of material from the pavement and occurs due to lose of asphalt content, weather condition, traffic condition etc and if this process started ones then it will be continue [Alvarez et al. 2006].

2.3.2 Freeze and Thaw Cycle

Freeze and thaw cycle was observed in the colder region in the porous pavement due to higher void ratio. Due to high voids content ice formation will occurred in voids and require more maintenance. It required deicer agent in cold countries and add cost to the project [Alvarez et al. 2006]. But maintenance of permeable bitumen pavement is less in comparison to dense bitumen road because permeable bitumen road with sub-surface has greater snow melting properties than dense road. Sub-surface or storage bed retains and absorbs heat which may melt light snow on porous pavement. During heavy snow deicer such as salt may be applied but should be non-toxic and pretreated salt should be applied.

Snow plowing must be done carefully by putting the blade at height than the normal height [Pennsylvania Stormwater Best Management Practices Manual]

2.3.3 Clogging

The surface layer of porous asphalt pavement has void content 18% to 25%, this make the surface more permeable and provides advantageous applications [Alvarez et al. 2006]. But debris and sediment from nearby area can close the voids in permeable bitumen pavement and decreases the functionality of pavement. So porous asphalt pavement should be avoided in the area of sand blown, wind erosion and also porous pavement should be avoided nearby hazardous waste area because it is very difficult to perform the hydraulic function and maintaining long term performance [Caltrans, Pervious Pavement Design Guidance August 2014]. A very excellent practice is needed for controlling the erosion and sediment on surface and storage bed of porous pavement. Surface sediment should not wash into the bed, they may be clean by the vacuum sweeper. Adjacent area to the permeable road must be maintained to prevent the wash out of soil into the porous pavement and if any wash out occur it should be immediately clean to prevent clogging of void. During inspection if any erosion and other deterioration is found, it should be instantaneously repaired [Pennsylvania Stormwater Best Management Practices Manual].

2.3.4 Cost

Cost of OGFC is 10 to 20% higher than the dense graded pavement due to addition of fiber [Alvarez et al. 2006, Pennsylvania Stormwater Best Management Practices Manual]. Life of porous asphalt pavement is between 50 to 100% of dense graded pavement [Alvarez et al. 2006, **18**]. Storage bed in porous asphalt pavement adds cost to it, but this cost is offset by reduction in drainage system required [Pennsylvania Stormwater Best Management Practices Manual]. Cost of porous pavement increases because it required more maintenance, any cracking, deterioration, erosion and growth of unwanted vegetation must be periodically maintained at least one time in a year. If any sand or dust is clogged into the void it must be removed as soon as possible when the surface is dry [New Jersey Stormwater Best Management Practices Manual]. Life of porous pavement reduces because

it has very less strength, durability and clogging of voids are the factors responsible for the life of porous pavement.

2.4 AREAS WHERE POROUS PAVEMENT SHOULD BE AVOIDED

The porous pavement should not be constructed in the areas where hazardous material are stored, where high risk of spill of toxic fluid is found, where high sediment is transported that may clog the void of surface, where local soil is clay, bedrock is proximity to pavement, water table is high and the area where sand blows [Kandhal et al. 2014, Caltrans, Pervious Pavement Design Guidance August 2014, New Jersey Stormwater Best Management Practices Manual]. Table 2.2 helps to determine which location is suitable for the pervious pavements. Category A, B and C are considered under pervious pavement and category D and E are not suitable for pervious road [Caltrans, Pervious Pavement Design Guidance August 2014]. Figure 2.12 shows the general specification required for permeable bitumen pavement for different types of layer [New Jersey Stormwater Best Management Practices Manual].

Table 2. 2 : Category of Porous Pavement

Category	Example	Loading	Speed	Risk
A	Landscaped area, sidewalks and bike paths	No vehicle load	N/A	Less
B	Parking area, park and ride areas, sidewalks and bike pathways	Low loads	Speed less than	Less
C	Rest areas and stations for maintenance	Medium loads	Less speed	Less
D	Low volume roads	Medium loads	High speed	Medium
E	Highways and weigh stations	High heavy loads	High speed	High

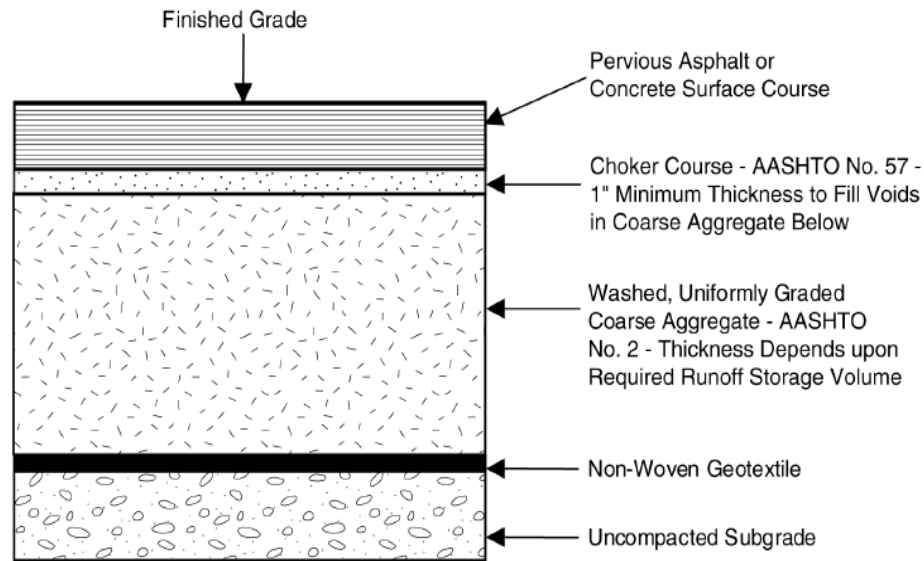


Figure 2. 12 : Typical Cross Section of Permeable Bitumen Pavement

2.5 DESIGN OF SURFACE LAYER

Surface layer is the top most layer of porous bitumen pavement structure. This layer has a thickness of (50mm to 100mm) typically 75mm [Kandhal et al. 2014, Schaus 2007]. The % of air void content is between 16% to 22% for free drainage of the water, whereas in dense graded asphalt pavement the percentage of air void content is ranging from 3% and 8%. Air void content lesser than 3% show rutting & air void content more than 8% may increase the oxidation and resulting in raveling or cracking [Schaus 2007, ASTM: D7064/D7064M]. Permeability of surface layer should be at least 100m/day [ASTM: D7064/D7064M]. Surface layer consist of aggregates, asphalt and additives which will be discussed in detail.

2.5.1 Material

The surface layer consists of aggregates, asphalt and fiber content. Properties of aggregates, asphalt and fiber is selected on the basis of following criteria.

Aggregate is selected based on some desirable properties. Tests which are performed to carry out the desirable properties of the aggregates are:

- i. For toughness or resistance to impact: Aggregate impact test
- ii. For hardness or resistance to abrasion: Los Angeles abrasion test
- iii. Resistance to get a smooth or polished surface: Polished stone value test
- iv. Resistance to crushing: Aggregate crushing test
- v. Durability or weathering test: Soundness test
- vi. Shape factor: Combined flaky and elongation indices test
- vii. Specific gravity and porosity: Specific gravity and water absorption test
- viii. Bonding between aggregate and bitumen: Stripping value test

High values of coarse aggregates are required to increase void content in surface layer. Coarser aggregates are those aggregates which retain on IS sieve 4.75mm. Coarse aggregates should be clean, durable, tough and uniform throughout [UNHSC 2009]. Coarser aggregates should have abrasion loss less than 30% in accordance to test method C131. Crushed gravel should have 90% particles with two faces and 90% particles with one face according to test method D5821. The flaky and elongated aggregates should not much more than 10 percent, with 5:1 to maximum to minimum size of aggregates [ASTM: D7064/D7064M]. Aggregates passing from IS sieve 4.75mm is referred as fine aggregates. Fine aggregates are very less in quantity as compared to coarser aggregates and must be clean, dust free and free from foreign particles [UNHSC 2009]. Percentage of air void content dependent on type of aggregates used [Tsai et al 2012].

Asphalt: Asphalt or bitumen consists of sulphur, oxygen and Chlorine. It is a viscous liquid which is hydrocarbon [Setyawan et al. 2017]. Now days polymer modified binder with different characteristics like aging resistance and plastic deformation can be used. Best adhesive with aggregates and good elasticity can be used as per requirement [Afonso et al. 2017]. The grade of asphalt is selected based upon environment, traffic condition and functional performance of porous asphalt pavement. Asphalt selected should be checked for penetration, viscosity and other conditions etc. Higher bitumen grade should be selected than the required grade of bitumen or PG grade bitumen are used to increase the

performance of permeable bitumenpavement. [ASTM: D7064/D7064M]. In permeable bitumen pavement durability and rut resistance are related to kinematic viscosity at 60⁰C of the bitumen. Bitumen with high kinematic viscosity result in high durability and rut resistance [Ma et al. 2018]. Moisture susceptibility will also be less with modified binder than with unmodified binder [Schaus 2007]. Mix design should have minimum 6% asphalt by total weight and traffic should be permitted to the porous pavement after 24 hours [Kandhal et al. 2014, ASTM:D7064/D7064M]. Figure 2.13 shows typical view of laying and compaction of porous asphalt pavement [Kandhal et al. 2014].



Figure 2. 13 : Typical View of Laying and Compaction of Porous Pavement

Filler: Due to more void in porous bitumen pavement, it has more chance to be affected by air and water. Air and water from environment cause oxidation of pavement and affect the binding properties of bitumen and aggregates and cause moisture loss in pavement. Adding fillers to the mixtures improve the stiffness of bitumen, strength of mixtures and various performance properties like permeability, stability, resistance to permanent deformation and resistance to moisture [Shukry et al. 2018]. The common filler material are lime, stone dust, fine sand, cement, ash, waste concrete dust and granite in powder form are used to bind the material [Sutradhar et al. 2015]. The most common used filler is lime and also known as active filler. Diatomite is also recommended to be used in the permeable bitumen pavement as filler.

Cantabro result was better with use of lime than diatomite. While other properties like moisture susceptibility and indirect tensile strength give better result with diatomite [Shukry et al. 2018].

Hydrated lime exists in bonded form cloudy and smoky shape. It has high content of calcium and oxygen and improves the bond between aggregates and bitumen. [Shukry et al. 2018].

Additives: Due to more air void content in the permeable bitumen pavement there may be problem of drainage of bitumen in the voids. The down ward movement of bitumen is prevented by addition of additive. A wide variety of additives like Cellulosic fibers, mineral fibers, synthetic fibers, glass fibers, carpet fibers and recycled tires fiber etc. may be added to decrease the drain down, prevent deformation and also prevent the excessive drain-down during transport and storage [Afonso et al. 2017, Mallick et al. 2000]. Other additive that can be used are DBS (polymer additive form Germany, include dibenzylidene sorbitol) and it is mixed with HVB at speed 4000rpm for 40 minutes. It was found that DSB increases the softening point and kinematic viscosity. So it was suggested that it can be used in high temperature areas for porous asphalt pavement and it decrease the durability and low temperature cracking resistance [Ma et al. 2018]. Addition of cellulosic fiber increase the bitumen percentage, retention of bitumen, better coating of bitumen with aggregates and result into better durability [Afonso et al. 2017]. Quantity of fiber to be added is 0.3% by total weight of mix and maximum permissible limit of drain-down value is 0.3% is suggested [ASTM: D7064/D7064M].

Anti stripping additive such as fatty amine or hydrated lime are added if (TSR) retained tensile strength is less than 80% [UNHSC 2009]. Abrasion loss, rutting and moisture susceptibility may be prevented by adding suitable polymer modified binder and fiber [Mallick et al. 2000]. Permeability of mix and resistance to permanent deformation also show better result with addition of cellulosic fiber [Afonso et al. 2017]. Thus we conclude that by using modified binder and fiber with appropriate gradation not less than FHAW can improve the characteristics of the OGFC mix [Mallick et al. 2000].

2.5.2 Gradation

Gradation of permeable bitumen pavement may be selected based on the criteria given below [Mallick et al. 2000, Tsai et al 2012].

- i. Highest V_a
- ii. $VCA_{MIX} \leq VCA_{DRY}$
- iii. $V_a \geq 18\%$

The above three mentioned conditions will ensure stone to stone contact of aggregates. The stone contact will define as, how the OGFC mixture will perform and existence of fine aggregate will define the stability of coarse aggregate structure. VCA_{DRC} depend upon aggregate type rather than gradation. Gradations for surface layer of porous asphalt pavement recommended by various codes are shown in Table 2.4.

Table 2. 3 : Various Gradations for the Design of Surface Layer of Porous Asphalt Pavement

Sieve Size (mm)	Percentage Passing ASTM	Percentage Passing NCAT 2000	Percentage Passing UNHC & NAPA
19.5	100	100	100
12.5	85-100	80-100	85-100
9.5	35-60	35-60	55-75
4.75	10-25	10-25	10-25
2.36	5-10	5-10	5-10
0.075	2-4	2-4	2-4

2.5.3 Optimum Asphalt Content

The optimization of asphalt can be achieved according to following criteria:

- a. Air void content, $18\% \leq V_a \leq 22\%$
- b. Drain-down test, maximum value 0.3%
- c. Cantabro test, maximum value 15% for dry sample and 30% for wet samples
[Mallick et al. 2000, Tsai et al 2012].

The initial binder content may be selected based upon the bulk specific gravity of combined aggregates CT 368 and AASHTO T 305 [Tsai et al 2012]. Aggregate type is the most important factor that affects the percentage of air voids content. Test result of air voids shows that more the bitumen content lowers will be air void [UNHSC 2009].

Due to more voids content and more bitumen content in the porous asphalt pavement, in summer bitumen tends to move downward and clog the voids, decrease the functioning of permeability, so draindown decide the maximum bitumen content [Masri et al. 2016]. Drain-down test result shows that percentage of drain-down increase with increase in binder content regardless the binder type and aggregate type. Mix containing AR binder has no drain-down and mix containing PG64-28PM has the highest draindown.

Cantabro test used to calculate raveling loss (loss of particle form surface due to many factors such as moisture content, temperature and aging) of dry and wet samples of porous asphalt pavements. This test determines the lower limit of optimum asphalt content [Masri et al. 2016]. Cantabro test shows that abrasion increases with increase in asphalt content and proved abrasion is dependent on binder type [UNHSC 2009]

2.5.4 Performance of Surface Layer

The permeable bitumen pavement is suitable for those areas where traffic load is very less like parking areas, sidewalks and pathways, urban roads and residential roads, cycle track, jogging areas, tennis court, tree grates in sidewalks and deck of swimming pool etc. As these pavement cannot bear heavy load, so these pavement need only permeability testing, indirect ITS testing, MIST, rutting testing and the creep test [Mallick et al. 2000].

Permeability: Permeability of mix will depend on voids in the mix and their interconnectivity. In permeability test air void are less important than their inter connection. Inter-connectivity of air voids can be determined by X-Ray tomography and image analysis. This study help in determining how the air voids are connected internally [Vardanega et al. 2012]. Samples was prepared with different aggregates gradation and different mineral composition, samples were scan with X-ray tomography and tested for permeability. It was

found that samples containing maximum aggregates size have high value of permeability and minerals composition do not affect the air voids connectivity [Król et al. 2018].

Permeability of laboratory samples can be determined by NCAT permeameter and ASTM 1701. ASTM method gave 75% lower value of permeability than the NCAT method. In permeability test silicone gel perform well in sealing the sample than plumbing putty [Li et al. 2013]. The minimum permeability required for surface course is 100m/day [ASTM: D7064/D7064M].

Indirect tensile strength: ITS provides measurement of elastic property for asphalt pavement. It gives an indication about resistance to failure of crack. The ITS value will be lower than the dense pavement due to porous nature of pavement, means in pavement aggregate-to-aggregate contact provides enhancement of strength of pavement. In addition to the strength of pavement this test also determines moisture damage of pavement based on ratio of dry TSR and wet TSR values [Masri et al. 2016]. MIST value should be at least 80% or additive may be added if value is less than the specified value [ASTM: D7064/D7064M]. In moisture damage test samples are conditioned at particular pressure, wet conditioning and temperature which will be similar to the actual road condition of pavement during traffic and wet conditioning [ASTM: D7064/D7064M].

Rutting: For determining the rutting value for porous asphalt pavement Hamburg wheel testing can be used. Due to more voids in porous asphalt pavement scattering and instability are the main problems. The rut resistance can also be carried out samples immersed in water for long time, this rutting resistance test is known as immersed rutting test and immersed rutting test indicate stripping value [Masri et al. 2015] following parameter were consider during rutting test. Rutting test was performed with 20000 wheel repetitions, rubber wheel diameter 200mm and width 50mm and tire pressure 700kPa was given on asphalt slab. Test was performed for 60 degree air bath and 40 degree water bath. It was concluded that rut resistance can be better by adding rubber bitumen [Yang et al. 2009]. Rutting test performed according to BS 589-110 code on slab of size 300*300*50 mm having 18-20% air void. Before test, slab kept in test temperature at least 6 hour and testing temperature was 45 degree Celsius and 8000 cycle was given to measure the rut

depth [Weiss et al. 2019, Ziari et al. 2015]. Average rut depth at 10000 passes and 20000 passes are used to find out the rut index. Rut index shows average loading passes required to reach a 1mm rut depth during 10000 to 20000 passes. More value of rut index excellent will be rut resistance of mix. Rut index can be calculated by the equation (2.1).

$$\text{Rut depth} = (20000 - 10000) / \left| \text{rut @ 20000} \right| - \left| \text{rut @ 10000} \right| \quad (\text{Eq. 2.1})$$

Parameter used:

Rut @ 20000 denotes absolute value of rut depth (mm) @ 20000 passes [Tsai et al 2012].

Dynamic creep test: To determine the rutting of bitumen mix. This method determines the permanent deformation potential of bitumen mixes based upon the axial compression test. The cycle on which plastic shear deformation exist is known as flow number. It indicates rut potential or rutting resistance, not rutting depth. Rutting resistance is related to permanent deformation versus cycles curve. A software was used UTM in which predefined parameter are put like temperature, pre load, contact pressure and number of cycles etc [Ziari et al. 2015, Weiss et al. 2019].

2.6 FILTER COURSE / CHOKER COURSE

Filter layer or choker layer is the second layer in porous asphalt pavement structure or choker course may also be provided differently in addition to filter course. It consists of crushed stone and placed on reservoir bed to stable it and facilitate surface bitumen porous layer [Kandhal et al. 2014]. Thickness of the filter course may vary depending upon the requirement of project. Thickness of filter course provided was 10-20cm [Tsai et al 2012] or 20 to 30cm [UNHSC 2009]. If additional choker course is provided its thickness may vary from 10 to 20cm [UNHSC 2009] or 25 to 50 cm [Kandhal et al. 2014]. The aggregate properties of filter course are:

Permissible Wash Loss is 0.5%

Permissible Durability Index is 35

Permissible Abrasion Loss

10% for 100 revolutions and 50% for 500 revolutions [Tsai et al 2012].

Thickness of choking layer in Jaipur was 50mm and compacted with 8-ton steel roller placed on reservoir layer and make it smooth so that surface course can be easily placed [Kandhal et al. 2014]. Gradation used for this layer was AASHTO NO. 57 aggregates according to UNHC or khandhal as shown in Table 2.5.

Table 2. 4: Gradation for Filter Layer AASHTO NO. 57

Sieve Size (mm)	Percentage Passing AASHTO No. 57
37.5	100
25	95-100
19	25-60
4.75	0-10
2.36	0-4

2.7 RESERVOIR LAYER

Reservoir layer is the third or last layer in design of porous asphalt pavement structure. As the name suggest this layer is made for storing water for short period of time. Voids percentage in this layer should be more than 40% and thickness of 225mm was considered [Kandhal et al. 2014, UNHSC 2009]. Aggregates size vary from 40mm to 75mm. Minimum thickness of 10cm may be adopted if reservoir layer act as capillary resistance for frost and heavy control or if underlying material below the reservoir layer is well drained [UNHSC 2009]. Reservoir layer thickness depends upon storage capacity, rainfall intensity which depends on topography of area and the underlying subgrade soil. Thickness of reservoir layer in Jaipur road construction was 365mm and compacted with 2 lift with 8 ton steel roller [Kandhal et al. 2014].

Water from roof may be directly attached to the reservoir layer of porous pavement which directly recharges the ground water table as shown in below Figure 2.14 [Kandhal et al. 2014].

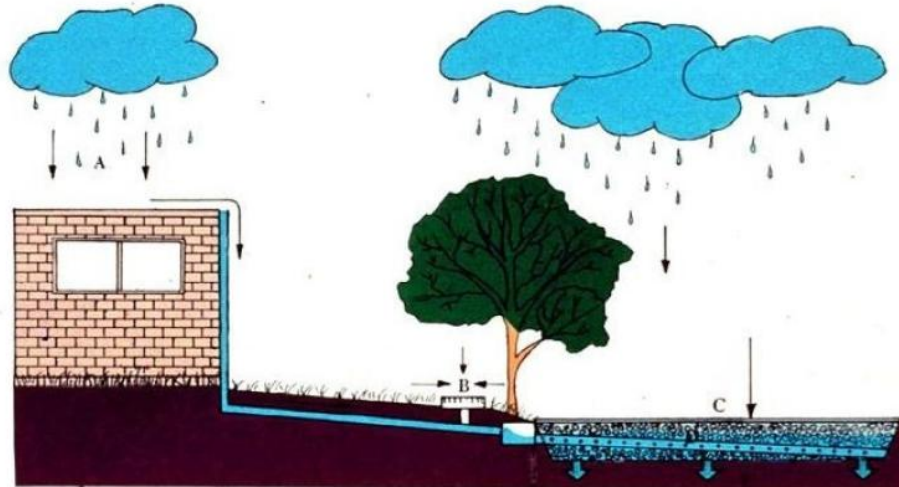


Figure 2. 14 : Roof Rainwater Harvesting Adjusted with Permeable Bitumen Pavement

In case of more rainfall, clogging of surface layer and more than maximum design flow emergency flow may be provided on side of pavement which is connected to the reservoir layer. The emergency flow is show in Figures 2.15 and Figure 2.16 [Kandhal et al. 2014, New Jersey Stormwater Best Management Practices Manual]. Water collected in the reservoir layer may directly percolate into the ground or in case may be collected by pipe system for further use [Kandhal et al. 2014, New Jersey Stormwater Best Management Practices Manual, FHWA 2015] Water must not stagnate more time in this layer because it will create anaerobic condition and this layer must be placed at least 2 feet above high ground water level. Permeability of subgrade should be minimum 0.5 inches/ hour and all the store water must be drain within 72 hours [Afonso et al. 2017]. Try to keep the layer slope invert flat for equal distribution of water but if needed does not exceed the slope more than 2% at reservoir invert [Caltrans, Pervious Pavement Design Guidance August 2014].

2.7.1 Gradation

Gradation used for reservoir layer was AASTHO NO. 3 size aggregates as shown in Table 2.6 [UNHSC 2009] and AASHTO NO. 2 size aggregates as shown in Table 2.7 [Kandhal et al. 2014].

Table 2. 5 : Reservoir Layer Gradation AASHTO NO. 3

Sieve Size (mm)	Percentage Passing AASHTO NO. 3 UNHC
63	100
50	90-100
37.5	35-70
25	0-15
12.5	0-5

Table 2. 6 : Reservoir Layer Gradation AASHTO NO. 2

Sieve Size (mm)	Percentage Passing
75	100
63.5	90-100
50	35-70
38	0-15
19	0-5
0.15	0-2



Figure 2. 15 : Close View of Extension of Reservoir Course for Overflow

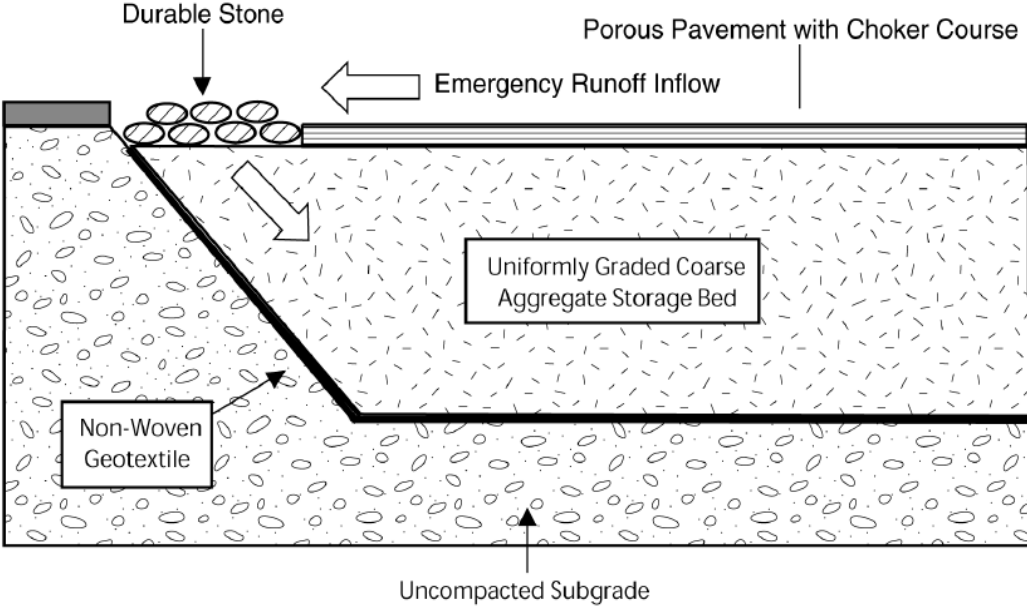


Figure 2. 16 : Emergency Flow in Porous Asphalt Pavement

When porous pavement is designed for light traffic, structural design is not significant, minimum thickness is designed by hydrological design as discussed below.

2.7.2 Hydraulic design

Porous bitumen pavement required hydraulic design for determining the thickness of porous bitumen pavement for infiltrating water, storing water and release the extra runoff from the reservoir layer. Hydraulic design of permeable bitumen pavement required rainfall and excess runoff data. For the hydraulic design of reservoir layer two methods are available SCS/NCRS Curve number method (CN) and Rotational method [FHWA 2015].

2.7.2.1 SCS/ NCRS CN Method

SCS/ NCRS CN method determine runoff volume that is generated by given rainfall. Runoff can be calculated by equation (2.2).

$$Q = (P - 0.2S) \wedge \frac{2}{P+0.8S} \quad (\text{Eq. 2.2})$$

Where

Q is the depth of runoff in inches

P is the depth of rainfall in inches

S is the highest retention of rainfall in inches

S depends upon the subgrade and surface characteristics of porous area by CN. S can be calculated by equation (2.3).

$$S = \frac{1000}{CN} - 10 \quad (\text{Eq. 2.3})$$

CN = Curve number (unitless)

CN tell about properties of drainage area that are generated by given rainfall. Subgarde soil is categories into four groups (A, B, C and D). Group A soil has high rate of infiltration and group D soil has lowest rate of infiltration. Table 2.8 shows soil group with rate of infiltration.

Table 2. 7 : Group of Soil for Hydraulic Design

Group	Type of Soil
A	High infiltration rate (greater than 0.3in/hr), like sand , loamy sand
B	Moderate infiltration rate (0.15 – 0.30 in/hr), like silt loam or loam
C	Low infiltration rate (0.05 – 0.15 in /hr), like sandy clay loam
D	Very low infiltration rate (less than 0.05 in/hr), like clay, sandy clay

Runoff depth (Q) is multiplied by drainage area for calculating the treatment volume. Table 2.9 shows runoff curve number in urban area for SCS method.

Table 2. 8 : Runoff Curve Number for SCS Method

Cover characteristics	Cover number (CN) for hydrological soil group			
	A	B	C	D
Impervious areas:				
Paved parking lots, roofs, driveways, etc	98	98	98	98
Streets and roads				
Paved; curbs and storm sewers	98	98	98	98
Paved; open ditches	83	89	98	98
Gravel	76	85	89	91
Dirt	72	82	85	88

SCS curve method should be applied separately first for pervious area and second for remainder area; resultant runoff volume is obtained from adding first and second runoff [NCDENR Stormwater BMP Manual].

2.7.2.2 *Outflow Rate and Volume Through Underdrain Pipe*

If the subgrade has low rate of infiltration which cannot percolate water with specific period of time then under drain pipe are required in reservoir layer. Outflow rate of under drain can be calculated by equation (2.4).

$$Q_u = k \times x \times m \quad (\text{Eq. 2.4})$$

Parameter used:

Q_u is the outflow of under-drain pipe, feet/hour

k is the coefficient of permeability of under-drain pipe, feet/hour

x = Area of under-drain

m = Underdrain pipe slope

After calculating outflow rate through each underdrain pipe, depth of reservoir course has to be calculated.

2.7.2.3 *Depth of Reservoir Layer*

Reservoir course can be calculated by equation (2.5).

$$D_p = N \left(D_c * R + P - \left(\frac{i}{2} \right) * t_f \right) - Q_u(t_f) / n \quad (\text{Eq. 2.5})$$

Where

D_p is the depth of reservoir course in feet

N is the number of under-drain pipes

Q_u is the outflow from under-drain pipe in feet/hour

D_c is the runoff depth contributing from drainage area in feet

R is the ratio of contributing drainage area to permeable paving surface A_p

t_f is the time to fill the reservoir course in day and can be taken as 0.083 day

i is the permeability of soil in feet/day

n is porosity, [Minnesota storm water manual]

Depth of reservoir layer can also be obtained from the following equation (2.6) given below by stormwater management guidebook, District Department of the Environment, District of Columbia.

$$D_p = \frac{\left\{ \left(P * R_v * \frac{D_a}{A_p} \right) - \left(i * \frac{t_f}{2} \right) \right\}}{n} \quad (\text{Eq. 2.6})$$

D_p = Depth of reservoir layer, feet

D_a is the contributing drainage area, including pervious pavement surface area (sf.)

A_p is the pervious pavement area (sf.)

P is the depth of rainfall (ft.)

R_v taken as 0.95, Runoff coefficient for impervious cover

i is soil permeability in ft/day

t_f is the time to fill the reservoir course in day and taken as 0.083 day

η_r is the effective porosity of reservoir course for stone No 57

2.7.2.4 Permeable Pavement Storage Volume

$$S_v = (D_p * \eta * A_p) + (i * t_f / 2) \quad (\text{Eq. 2.8})$$

where

S_v is the Storage volume of reservoir layer in ft^3

D_p is the reservoir layer depth in ft

η is the effective porosity and can be taken as 0.35

A_p is the porous area of road in ft^2

i depend on infiltration rate of the soils and unit is ft/day)

t_f denotes the time to fill the bottom layer in day and can be chosen as 0.083 day [Stormwater Management Guidebook, District of Columbia]

Porous pavement carrying truck load, the structural design code AASHTO 93 has to follow. Recommended layer coefficient for different layer of porous asphalt pavement is shown in Table 2.10 and minimum recommended thickness of permeable bitumen pavements shown in Figure 2.17 [FHWA 2015].

Table 2. 9 : Layer Coefficients

Material Layer	Structural Coefficients
Permeable Bitumen	0.40 – 0.42
Bitumen Treated Porous Base	0.30 – 0.35
Reservoir Layer	0.10 – 0.14

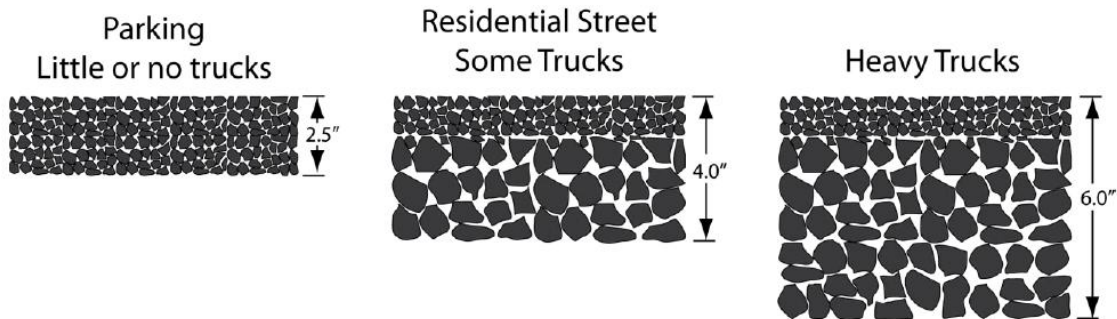


Figure 2. 17 : Minimum Recommended Compacted Permeable Bitumen Pavement Thickness

2.8 GEOTEXTILE / FILTER LAYER / FILTER BLANKET / OPTIONAL BOTTOM LINER

Geotextile fiber and fabric are not suggested to use at the bottom permeable bitumen pavement because these get clogged shortly [Tsai et al 2012]. A non woven geotextile may kept in between subgrade and reservoir course so that subgrade particles do not migrate into

the stone reservoir bed [[Kandhal et al. 2014, Abustan et al. 2012]. It is provided on the sloping side of porous asphalt pavement and not provided at the bottom of the pavement unless structurally needed [UNHSC 2009]. Geotextile decreases the rut depth, breakage and maintain a good serviceability [Abustan et al. 2012].

A Non-Woven Geotextile fiber Mirafi160N consist of polypropylene fiber and inert biological degradation, resist acids, alkalis and other chemical attacks. Properties of non-woven geotextile fiber are in Table 2.11 [UNHSC 2009].

Table 2. 10 : Properties of Non-Woven Geo-textile Fiber

Properties of Geotextile	ASTM Code	Unit	Minimum average roll values (MD)	Minimum average roll values (CD)
Tensile Strength	D4632	KN	0.71	0.71
Tensile Elongation	D4632	%	50	50
Mullen Burst Strength	D3786	KPa	2100	2100
Puncture Strength	D4833	KN	0.42	0.42
Apparent Opening Size	D4751	Mm	0.212	0.212
Permeability	D4491	Cm/sec	0.22	0.22
Flow Rate	D4491	lpm/m ²	4.477	4.477

Filter course may also be provided with thickness range of 20-30cm, consisting of poorly graded course sand. It should have a hydraulic conductivity or coefficient of permeability 10 to 60 ft/day without no over compaction [UNHSC 2009]. A stone filter

course of thickness 10mm to 25mm was provided in jaipur road construction and thickness 75mm this layer is compacted with light steel roller of 2 ton [Kandhal et al. 2014].

Filter blanket may also be provided with thickness 8cm to prevent the migration of the particle from the filter layer to reservoir layer. Stone used in the filter layer material must be between filter layer aggregates and the bottom course aggregates [UNHSC 2009].

2.9 SUBGRADE

Subgrade is the soil below the reservoir layer and it should be investigated by boring a test pit for permeability, water depth and bed rock depth. Porous pavement is not suitable for clayey soil, high water table and near bed rock. Subgrade should be uncompacted and no heavy equipment is allowed on uncompacted subgrade so that its permeability does not get reduce. Subgrade should have minimum permeability value 12.5mm per hour [Kandhal et al. 2014]. Permeability of soil should be such that it percolates water from reservoir layer within 72 hours. Subgrade is almost flat or a slope of 5% is acceptable, which ensures that water will not flow and it will directly penetrate into the ground [Kandhal et al. 2014]. Permeability of soil found in jaipur road construction was 46.5mm per hour and is more than the recommended permeability of 12.5mm per hour [Kandhal et al. 2014]. Clayey soil should be avoided for the subgrade and subgrade should be far away from the hazardous site and sewer line. Between soil and the subgrade a filter course / filter blanket / Optional bottom liner / geotextile may be provided to control the migration of the soil particle from the subgrade to the reservoir layer as explained above.

2.10 OUTCOMES OF POROUS PAVEMENT

Properties like porosity, permeability and density of uniform graded permeable bitumen pavement is found better as compared to well graded porous bitumen pavement. But the properties related to strength, stability and tensile strength of well graded porous asphalt pavement is found better than then uniform graded porous asphalt pavement. So uniform graded porous asphalt pavement cannot meet the strength characteristics and it is recommended for low volume roads [Setyawan et al. 2017]. Applications of porous

pavements are very few because these cannot be used for heavy loads [FHWA 2015, Abustan et al. 2012]. These are used mostly for:

- I. Low volume roads
- II. Parking areas
- III. Sidewalks and pathways
- IV. Urban roads and residential roads
- V. Cycle track
- VI. Jogging areas
- VII. Tennis court
- VIII. Tree grates in sidewalks
- IX. Deck of swimming pool

Permeable bitumen road at parking lot just after rain is shown by Figure 2.18 [Kandhal et al. 2014].



Figure 2. 18 : Shows the View Just After Rain

In Figure 2.19 permeable bitumen pavement and conventional pavement are shown during the rain at highway in Arizon [Kandhal et al. 2014].

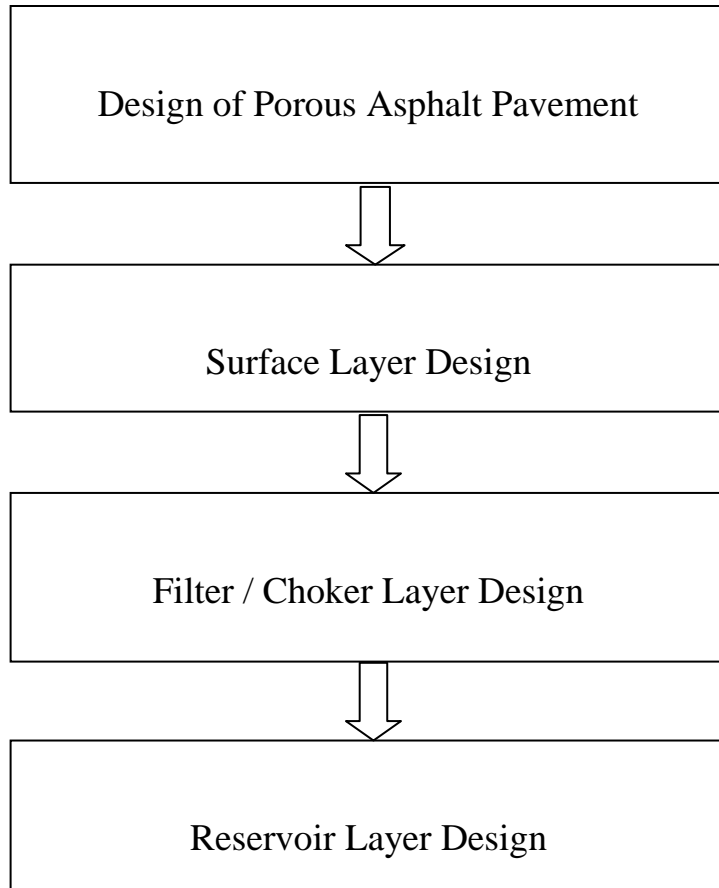


Figure 2. 19 : Shows the View During Rain

Left side pavement is porous and the right one is conventional asphalt pavement (Highway in Chandler, Arizona). After 20 years of service the porous pavement is still functioning well. [Kandhal et al. 2014].

CHAPTER 3 EXPERIMENT METHODOLOGY

Overall methodology employed in design of porous asphalt layers is described in chapter three. The overall methodology was categorized in three parts. First part include design for surface layer of porous asphalt pavement, second part included design of filter layer / choker layer and third part included design of reservoir layer as shown below:



3.1 SURFACE LAYER

Design of surface course for porous asphalt pavement was divided into four sections. The four section of surface layer are; selection of material, selection of gradation, optimum bitumen content and performance test. Complete methodology of surface layer design is shown below in Flow Diagram 3.1.

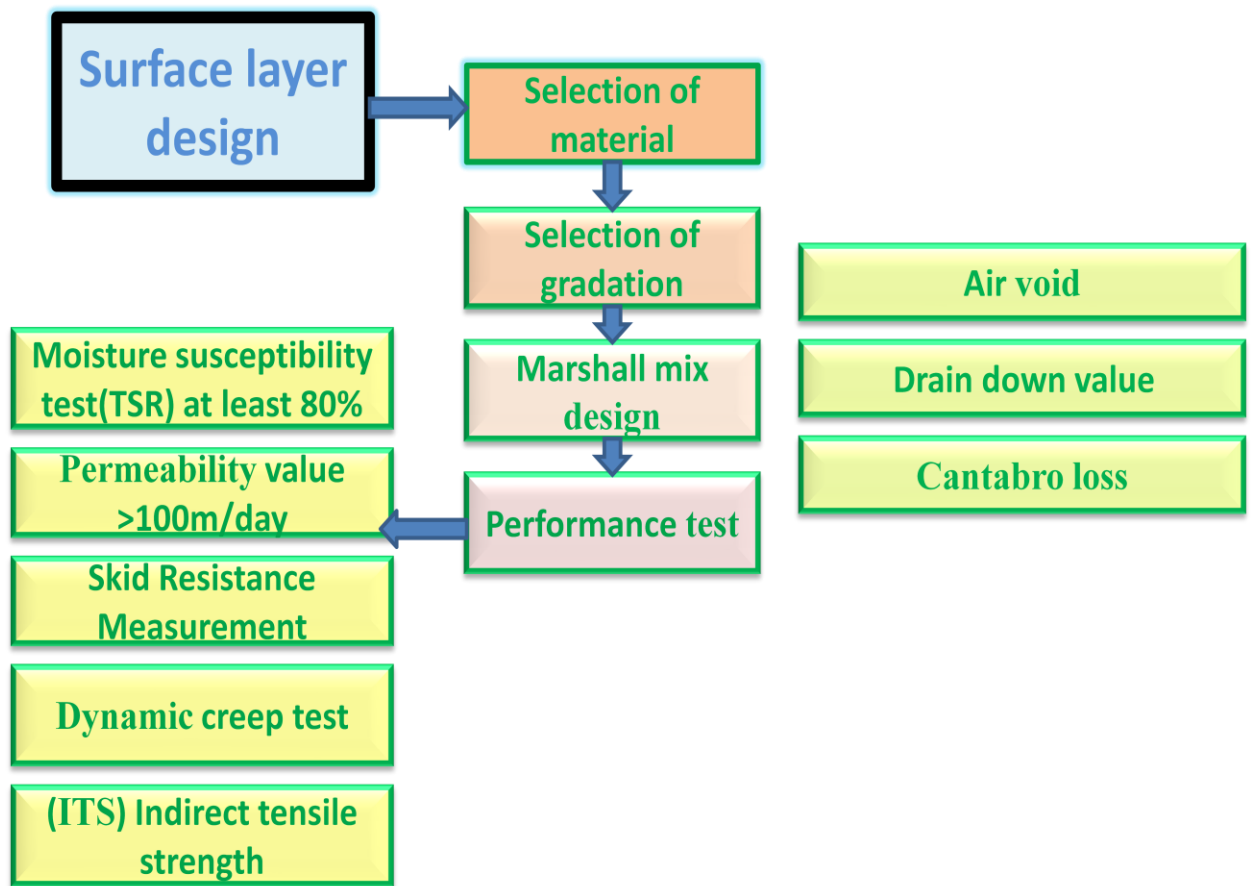


Figure 3. 1 : Methodology for Surface Layer Design

3.1.1 Selection of Material

3.1.1.1 Aggregates

Aggregates were selected based on laboratory tests required for the designing of surface layer in permeable bitumen road. In this permeable bitumen road project aggregate impact test, Los Angeles abrasion test, specific gravity and water absorption test, shape test and stripping value test have been performed.

Impact test was performed to obtain impact value of aggregates for the toughness property of aggregates. Toughness is the characteristics of aggregates to sudden impact. The

moving vehicle will give the sudden impact to the aggregate which results into the breaking of the aggregates into smaller pieces. This test was performed as per IS- 2386 part IV. Permissible impact value for the pavement is 30% as per MOTRTH 2013 specification.

Shape test was done for determining the shape of aggregates. These particles possess less interlocking and hence create problem during compaction. For base and sub-base course, these are not suitable because under heavy load these particles get break. This test was conducted as per IS- 2386-I and maximum value for combined flakiness and elongation index is 35% as per MORTH 2013 specification.

The specific gravity of an aggregate determines the strength or quality of the material. If the specific gravity of aggregate is higher, it will have higher strength. Water absorption tells about the strength of aggregate. Aggregates with more water absorption have more voids in structure and avoided for use unless they are checked for strength, impact and hardness tests. This test was conducted as per IS-2386 part3. The permissible specific gravity of the aggregate used in road construction is in the range of 2.5 to 3.2 with the average value of 2.7. The maximum water absorption Value for the surface course is 1% to 2%.

Abrasion determines the resistance to wear or hardness. Vehicle movements affect the surface aggregates and subject them to wearing action. Wheel of vehicles and aggregates come in contact at surface layer and cause abrasion. This test was performed according to I.S.-2386 part-IV and maximum permissible value of abrasion loss is <30%.

The stripping occurs due to the greater attraction of the aggregate with water than the bitumen. Several anti-stripping agents are also available which may reduce stripping of bitumen from aggregate. This test was conducted as per IS- 6241-1971 and maximum permissible value as per MORTH, 2013 is 5%. Figure 3.2 shows a close view of 20mm, 10mm size stone aggregates with stone dust used under this research work.



20mm Aggregates

10mm Aggregates

Stone dust

Figure 3. 2 : Close View of Aggregates Used Under Present Research Work

3.1.1.2 Bitumen

Bitumen proposed to be used in the execution of works should have sufficient viscosity or fluidity. In this project VG30 bitumen was used. The various test performed on the collected asphalt sample are penetration test, ductility test, viscosity test and softening point test.

Penetration test: Penetration test determines the consistency of asphalt for grading the bitumen. This test measures the depth of penetrating needle in a unit of one-hundredth of cm. 80/100, 60/70 and 30/40 are three penetration grades of bitumen. 80/100 denotes the penetration range of bitumen between 80 and 100. Higher penetration value is generally chosen in the colder climate. This test was performed according to IS- 1203-1978 and minimum penetration value for the bitumen of grade VG30 at 25⁰C is 45.

Softening point test: This test denotes the temperature at which asphalt has equal viscosity. Asphalt with a high softening point is preferred in hot places. This test was performed according to IS 1205-1978 and minimum value of softening point for VG30 is 47⁰C.

Viscosity test: Penetration grade asphalt has been replaced by the viscosity grade of asphalt because of more reliability. Viscosity is the property of a fluid that measures resistance to flow of liquid. Low and high viscosity during compaction and mixing result in low stability value. At high viscosity, it resists the compactive effort and results into the

heterogeneous mix and at low viscosity, the mix will lubricate instead of providing the uniform mix. The range of viscosity depends on the type and grade of binder and the temperature of application. This test was conducted as per IS: 1206-1978 and minimum kinematic viscosity at 135⁰C in centistokes is 350 for VG30.

Ductility test: Asphalt must form a thin film around the aggregates so that it does not crack and improve the interlocking of the aggregate. Bitumen with low ductility gets cracked under repeated application of load. Ductility of a asphaltic material is determined by the distance in centimeters to when standard specimen of asphaltic sample is pulled under standard test condition. This test was performed according to IS- 1208-1978 and minimum ductility value for the VG 30 at 25⁰C is 40cm.

3.1.1.3 Additives and Fillers

In this study filler materials used were stone dust and lime. Stone dust used was passing from 0.075mm IS sieve. The percentage of stone dust and lime used in mix was 1% and 2% of total mix. The increasing demands of performance of road and to meet the required properties of mix additive are used. In this study two type of fiber had been used named as pellet fiber and cellulosic fiber for comparing the properties of porous asphalt mix.

The pellet fiber used was designed by JRS and fully named as VIATOP premium das pellet fiber as shown in Figure 3.3.. This fiber is mixed of 90% by weight (ARBOCEL ZZ8/1) and 10% by weight of bitumen 50/70.



Figure 3. 3 : Pellet Fiber

3.1.2 Selection of Gradation

Gradation for surface layer was selected based on three criteria, void content should be highest and minimum of 18% void should be selected, VCA_{mix} should be less than or equal to VCA_{dry} . Selection of gradation for surface layer has been done as per flow diagram given in Figure 3.4.

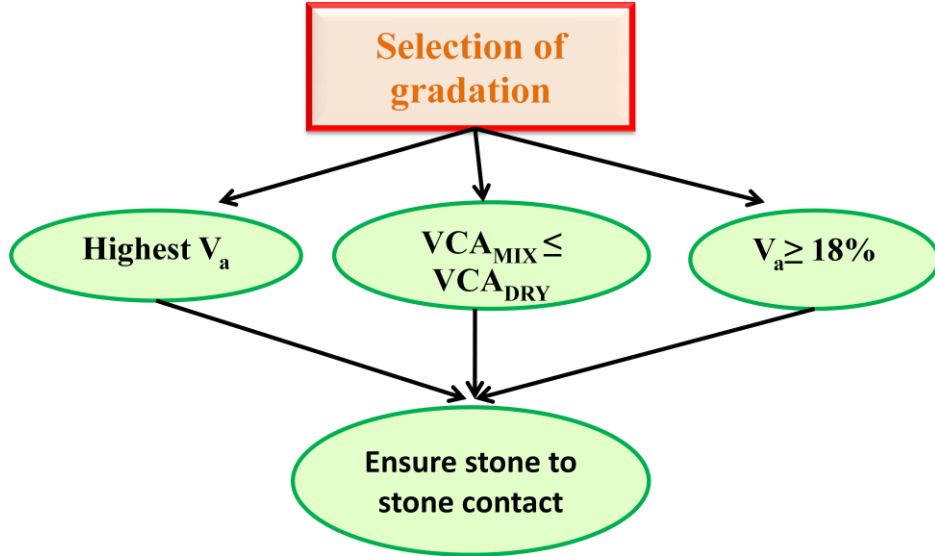


Figure 3. 4 : Selection of Gradation

Where:

V_a = Air void content and calculated by equation (3.1)

VCA_{mix} = Void in coarse aggregate in the mix can be calculated by equation (3.2)

$$V_a = 100(1 - Gmb/Gmm) \quad (\text{Eq. 3.1})$$

$$VCA_{MIX} = 100 - Gmb * \frac{Pca}{Gca} \quad (\text{Eq. 3.2})$$

G_{mm} denotes highest specific gravity of separated mix aggregates obtained from AASHTO T209 (rice apparatus test) and it is discussed in section dealing with determination of optimum asphalt content for permeable bitumen mix.

G_{mb} denotes the bulk specific gravity of compacted mix aggregates obtained from AASHTO T331 (core look apparatus test) and it is discussed in section dealing with determination of optimum bitumen content for porous bitumen mix.

P_{ca} denotes the percentage of coarse aggregates

VCA_{DRC} = Void in dry rodded condition can be calculated by equation (3.3)

$$VCA_{DRC} = \left(\frac{G_{ca} * \gamma_w - \gamma_s}{G_{ca} * \gamma_w} \right) * 100 \quad (\text{Eq. 3.3})$$

G_{ca} denotes bulk specific gravity of coarse aggregates

γ_w denotes unit weight of water (998kg/m³)

γ_s denotes unit weight of coarse aggregates in dry rodded condition (kg/m³)

In VCA_{DRC} , γ_s was calculated based on test method C29/C29M method.

Selection for Mix Gradation: The selected gradation of the mix was based on the ASTM (American Standard of Testing and Material), NCAT 2000 Gradation (National Center of Asphalt Technology), UNHC Gradation (University of New Hampshire Stormwater Center) and NAPA Gradation (National Asphalt Pavement Association). The detail of each specified gradation and selected gradation are given in Table 3.1 to 3.3 respectively..

Table 3. 1: ASTM Gradation

Sieve (mm)	% Passing			% Retained
	Lower limit	Upper limit	Selected gradation	
19.5	100	100	100	0
12.5	85	100	92.5	7.5
9.5	35	60	58	34.5
4.75	10	25	15	43
2.36	5	10	7.5	7.5
0.075	2	4	3	4.5
Pan				3

Figure 3.5 shows selected gradation of mix, which falls in between suggested ASTM gradation guidelines.

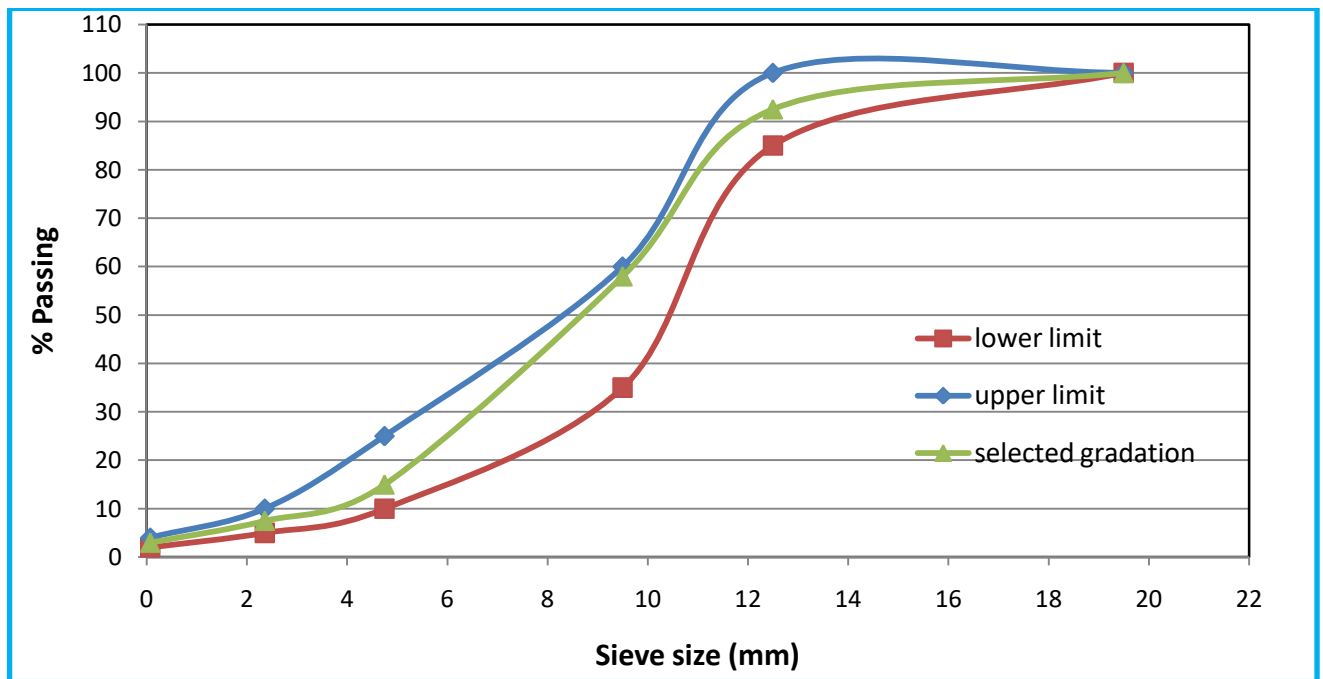


Figure 3. 5 : Selected Gradation v/s ASTM Gradation

Table 3. 2 : NCAT 2000 Gradation

Sieve (mm)	% Passing			% Retained
	Lower limit	Upper limit	Selected gradation	
19.5	100	100	100	0
12.5	80	100	92.5	10
9.5	35	60	58	32
4.75	10	25	15	43
2.36	5	10	7.5	7.5
0.075	2	4	3	4.5
Pan				3

Figure 3.6 shows selected gradation of mix, which falls in between suggested NCAT2000 gradation guidelines.

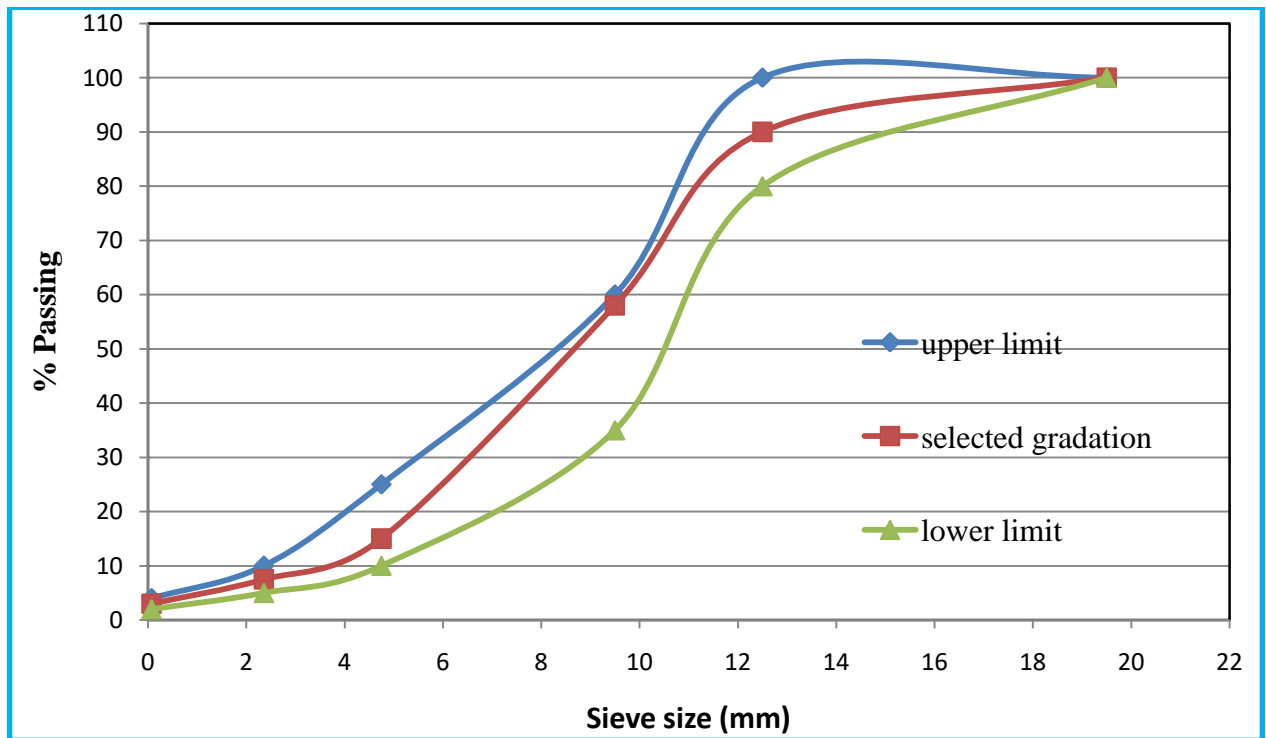


Figure 3. 6 : Selected Gradation v/s NCAT 2000 Gradation

Table 3. 3: UNHC & NAPA Gradation

Sieve (mm)	% Passing			% Retained
	Lower limit	Upper limit	Selected gradation	
19.5	100	100	100	0
12.5	85	100	92.5	7.5
9.5	55	75	58	34.5
4.75	10	25	15	43
2.36	5	10	7.5	7.5
0.075	2	4	3	4.5
Pan				

Figure 3.7 shows selected gradation of mix, which falls in between suggested UNHC & NAPA gradation guidelines.

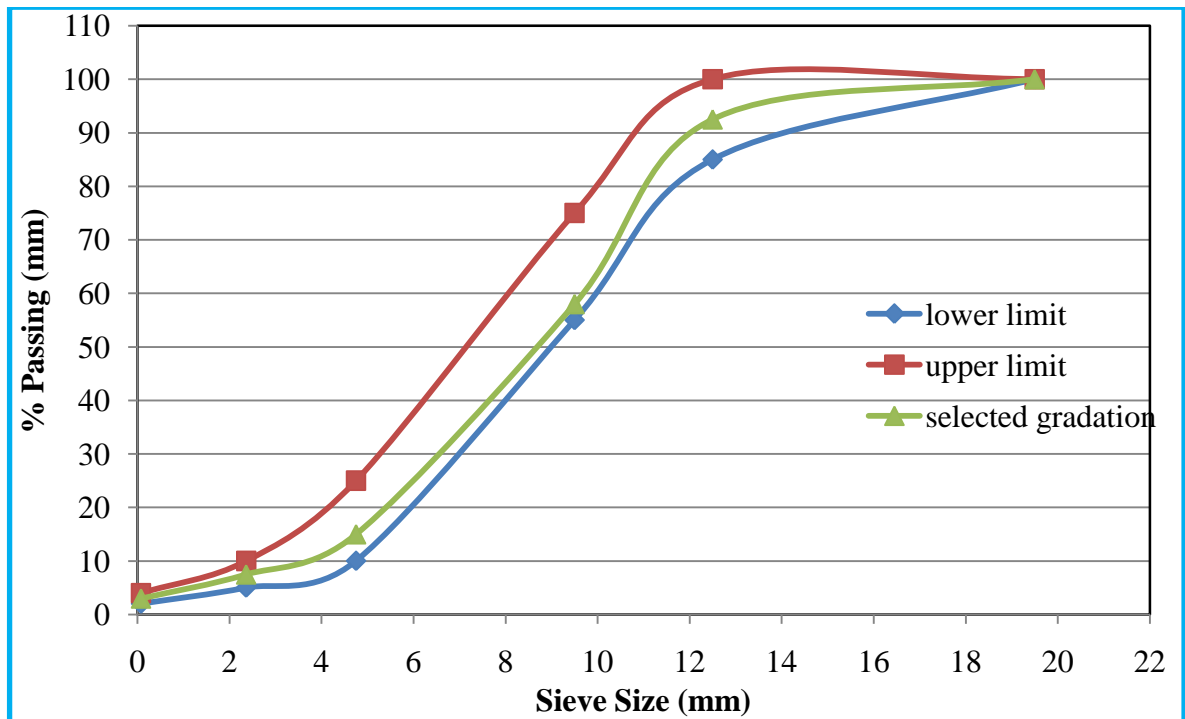


Figure 3. 7 : Selected Gradation v/s UNHC & NAPA Gradation

3.1.3 Samples Preparation

Samples were prepared for testing through Marshall Machine and preparations of samples are shown by flow diagram as shown in Figure 3.8. Each sample required approximately 1200gm aggregates and taken according to the gradation, including 2% lime and 1% stone dust. Initial bitumen content was selected according to the literature review which was 5% and thereafter two more binder content viz. 5.5% and 6% was taken under the present work. Fiber content used was 0.3% by weight of the mix. 159⁰C and 148⁰C were mixing and compaction temperature which were obtained from the temperature viscosity curve and shown in Figure 3.9. At each binder content, the samples were prepared at 30, 40, 50 blows of marshal hammer to both sides of samples.

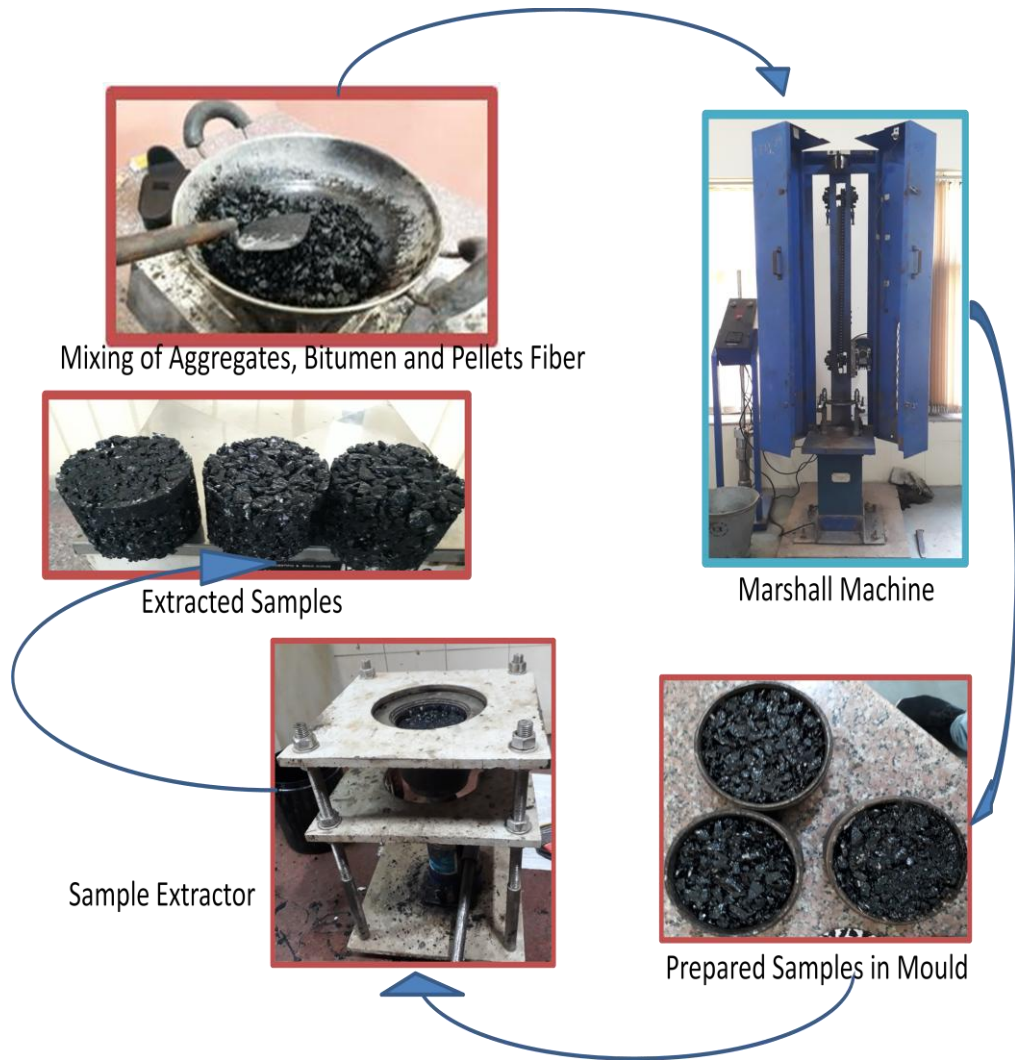


Figure 3. 8 : Flow Process of Making Marshall Samples

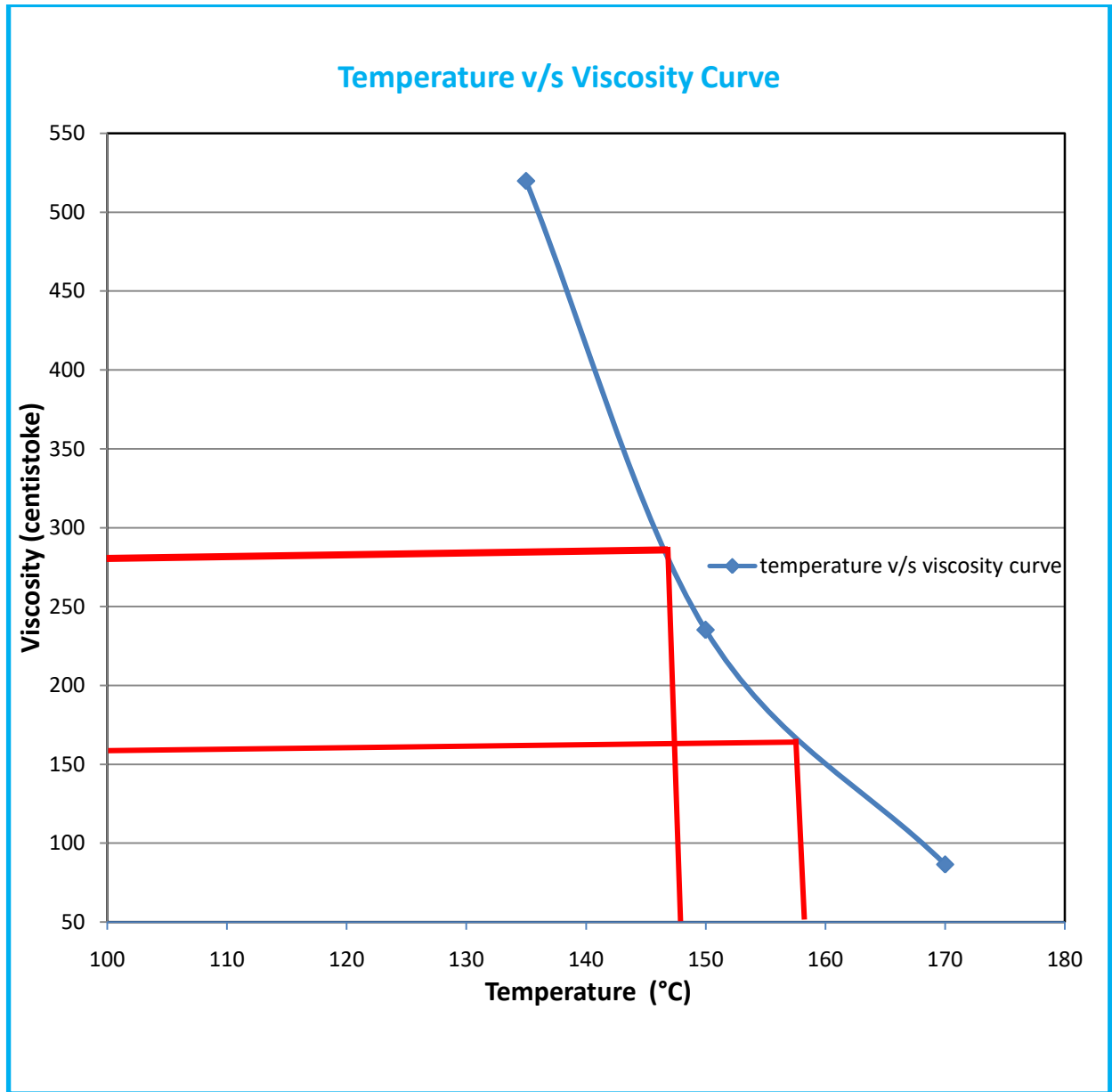


Figure 3. 9 : Mixing and Compaction Temperature Graph

Methodology adopted to calculate optimum voids content for porous asphalt mix are shown through flow diagram in Figure 3.10.

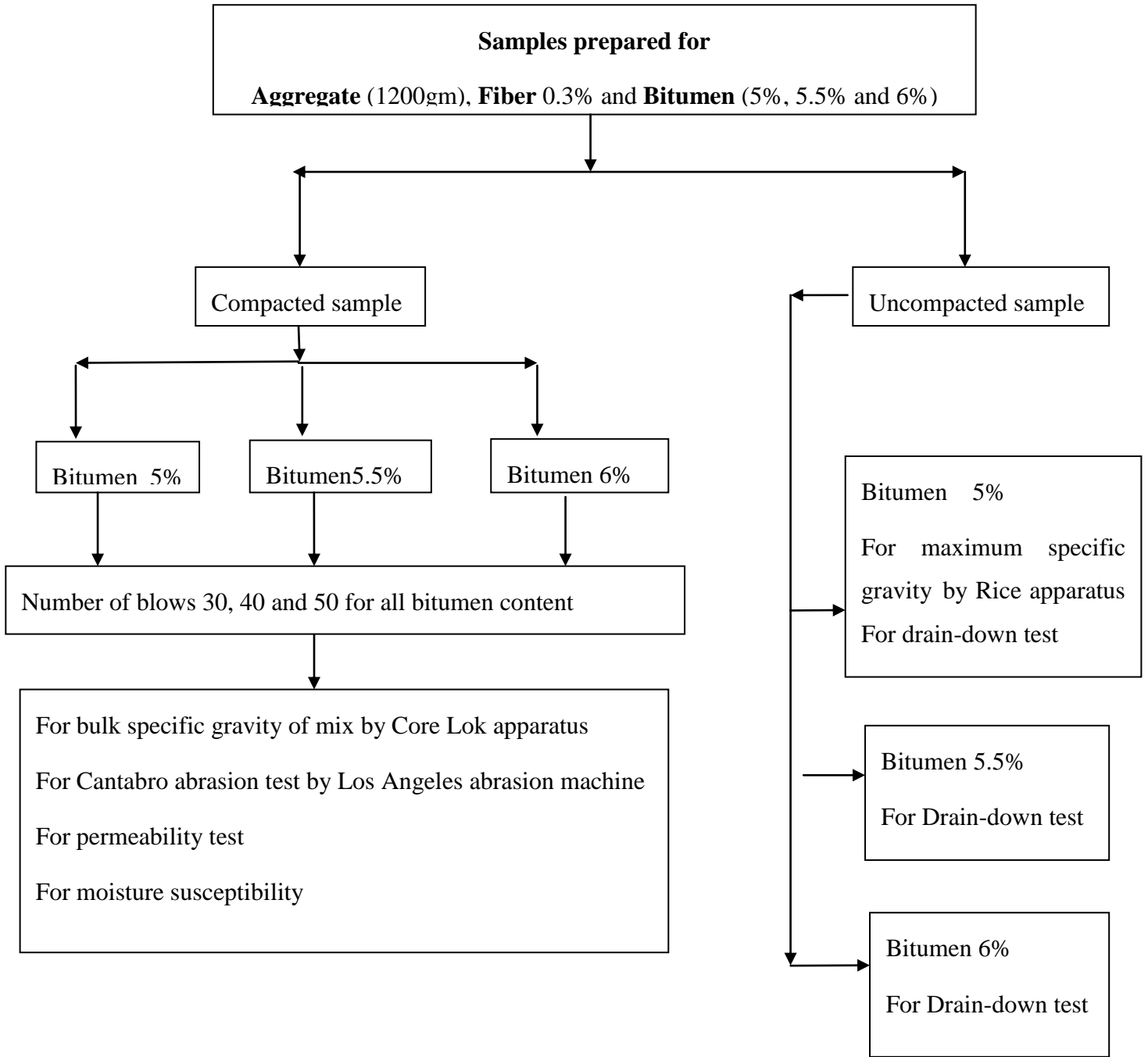


Figure 3. 10 : Methodology for Selection of Optimum Binder Content

3.1.4 Optimization of Bitumen

Bitumen was optimized according to three criteria i.e air void content, drain-down value and the cantabro loss. Figure 3.11 shows permissible values for three criteria.

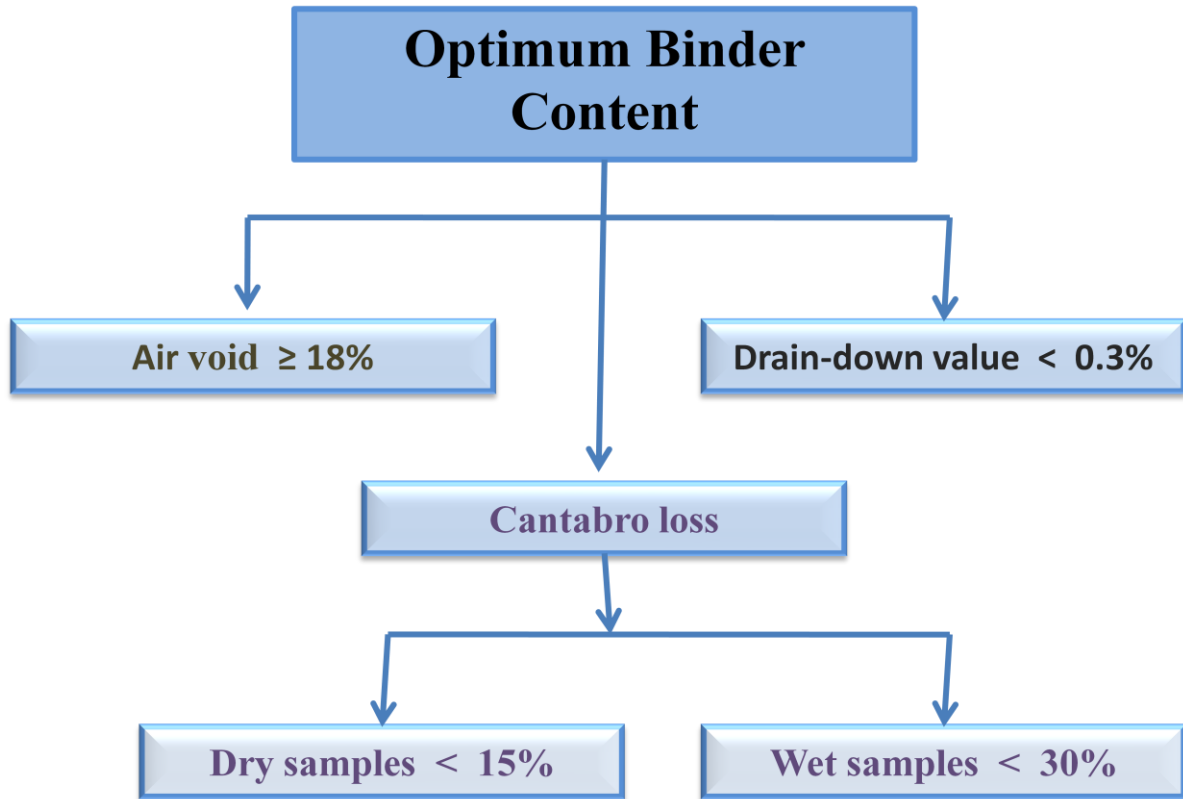


Figure 3. 11 : Design Criteria for Optimization of Bitumen Content in Permeable Bitumen Mix

3.1.4.1 Air Void Criteria

Air void criteria required:

- The maximum specific gravity (Gmm)
- The bulk specific gravity (Gmb)
- The air void should be at least 18%

Maximum Specific Gravity by Rice Apparatus

This test was performed according to AASHTO T209, for determination of maximum specific gravity of loose mix samples by Rice Apparatus as shown in Figure 3.12.

Loose samples were prepared and spread to cool at room temperature Figure 3.13. Weighted specimens were placed in the mould and water was added at about 25⁰C for covering approximately 2.5mm of sample. Lid was kept on the container and entrapped air was removed from the container by partially vacuum 3.7+/- 0.3 kpa residual pressure for 15+/- 2 minutes. Container was agitated manually for 2 minutes to facilitate removal of air and vacuum was released, the pressure was increase to atmospheric pressure in 10-15 second, the vacuum pump was switch off and lid was take away. Container was filled to overflow level at 25⁰C±1⁰C and water is allowed to stabilize and finally weight of bowl and content immersed in water was determined. Maximum specific gravity was determined by equations (3.4) and (3.4).

$$G_{mm} = \frac{A}{A-C} \quad (\text{Eq. 3.3})$$

$$G_{mm} = \frac{A}{A_{SSD}-C} \quad (\text{Eq. 3.4})$$

Parameter used:

A denotes, dry sample weight in air, g

C denotes, submerged weight of the sample in water in g

A_{SSD} denotes, weight of saturated surface dry sample in the air in g

Theoretical maximum density (kg/m³) = G_{mm}*997.1

Maximum Specific Gravity at Other Binder Content can also be calculated by equation (3.5).

$$G_{mm} = \frac{100}{\frac{P_s}{G_{se}} + P_b/G_b} \quad (\text{Eq. 3.5})$$

Parameters used:

G_{mm} denotes, intense specific gravity at other binder content

P_s denotes, aggregate percentage by the total mix of aggregate

G_{se} denotes, effective gravity of mix

P_b denotes, percentage of the binder by total mix weight

G_b denotes, specific gravity of bitumen

Effective specific gravity obtained using equation (3.6).

$$G_{se} = \frac{P_s}{\frac{100}{G_{mm}} - P_b/G_b} \quad (\text{Eq. 3.6})$$

Parameters used in equation are similar as discussed above.



Figure 3. 12 : Rice Apparatus



Figure 3. 13 : Separated Aggregates

Bulk Specific Gravity by CoreLok Apparatus

This test was performed according to AASHTO T331, for the calculation of bulk specific gravity of the sample with water absorption more than 2%. Figure 3.14 shows flow process of Corelok Test. Initially weight of dry sample and plastic bag was taken. Bag was placed inside the chamber on sliding plate and sample with smoothest side was kept in the bag. Chamber and bag air was removed by vacuum system provided in the machine. Sealed samples was taken out from the chamber and weighted in air and water. Bulk specific gravity value was calculated by equation (3.7)

$$\text{Bulk specific gravity} = \frac{A}{[C+(B-A)]-E \cdot \frac{[B-A]}{F}} \quad (\text{Eq. 3.7})$$

Where

A = Initial dry weight of sample in the air in gm

B = dry sealed sample in gm

C = weight of specimen after removal from the seal in gm

E = weight of sealed sample in water in gm

F = apparent specific gravity of plastic bag

The bulk specific gravity was determined by the core gravity software. Here all the values of bulk specific gravity and air void content are calculated by the software.

Plastic bags were selected on basis of the following properties:

- i. Small bag, minimum opening 9.25in. and maximum opening 10.25in. with a weight less than 35gm.
- ii. Large bag, minimum and maximum opening 14.75in. and 15.5in respectively with a weight 35gm or more.
- iii. Should have puncture resistance.
- iv. Should have stand-in temperature of 158⁰ F.
- v. Impermeable of water.

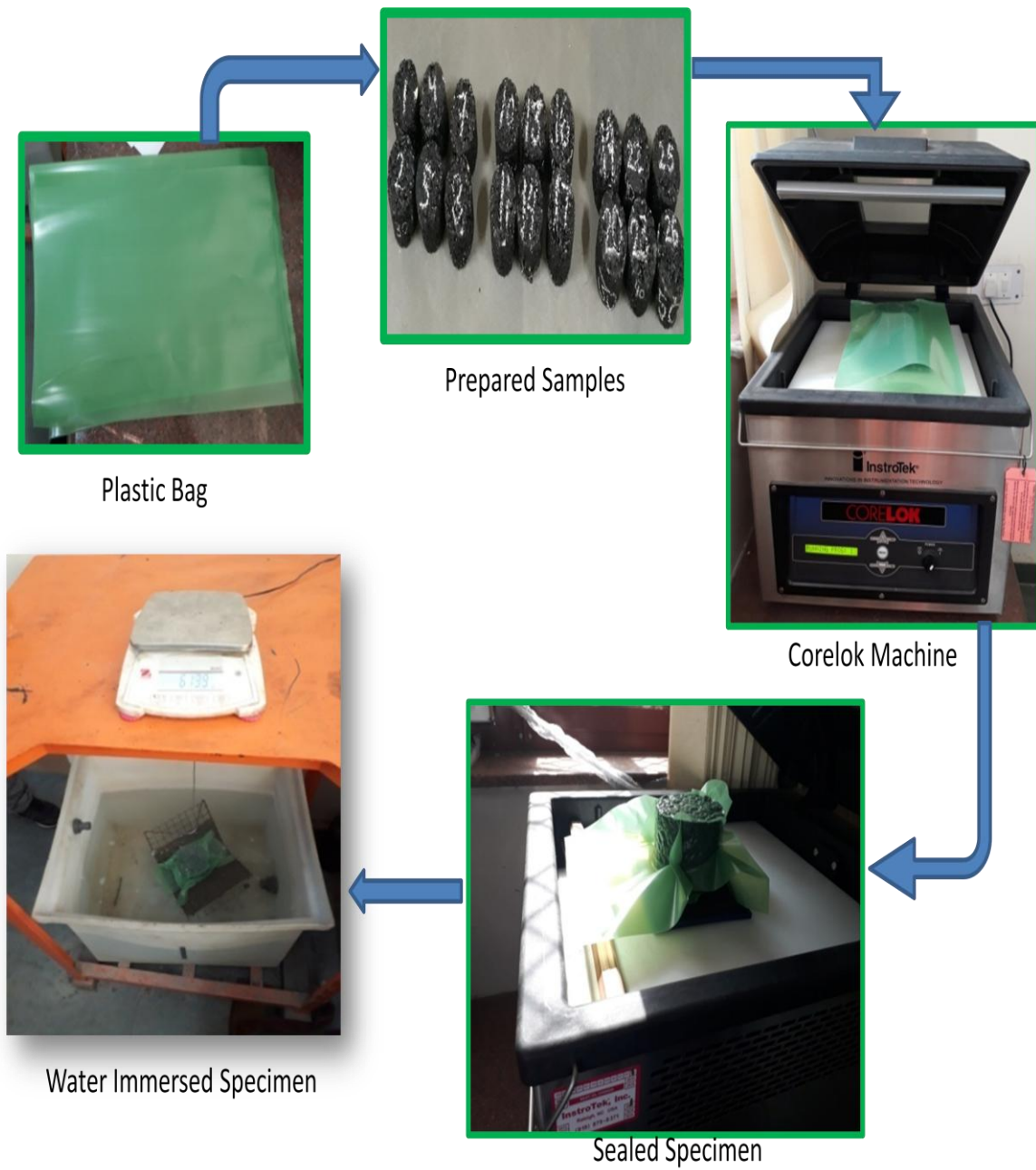


Figure 3. 14 : Flow Process of Core-Lok Test

3.1.4.2 Drain-down Test (AASHTO T 305)

This test was performed according to test method AASHTO T 305. Draindown is that part of the mix which apart itself from the mix and flow as downward through the mixture. To find out the drain-down value, a loose mix sample was prepared and separated after sufficient cooling. Cooled sample was placed in the standard tare basket and tare tray (as shown in Figure 3.15). Weight of tray and basket was also noted. Basket and the tray were kept in the oven at plant production temperature for a period of 1hour+- 5 minutes. After a specified time drain-down basket was taken from oven and weight of tray was measured. Draindown value was determined based on the equation (3.8). The drain- down value should not more than 0.3%

$$\text{Drainage} = \frac{A-B}{C} * 100 \quad (\text{Eq. 3.8})$$

Parameters used in equation 3.8 are:

A denotes, final weight of container, g

B denotes, initial weight of container, g

C denotes, initial sample weight, g



Figure 3. 15 : Drain-down Basket

3.1.4.3 Cantabro Test (Tex-245-F)

Cantabro test was performed according to Tex-245-F, to find out the abrasion loss of compacted bitumen sample. Cantabro test measures the breakdown pieces of the individual with the help of Los Angeles abrasion testing machine as shown in Figure 3.16. The percentage of weight loss indicates the durability of the porous friction course which relates the quantity and quality of bituminous mixes used in the compacted specimen. Cantabro test was conducted on both dry and wet samples.

Initially compacted samples were weighted and samples were placed in the machine one by one with no steel balls. 300 revolutions for 30-33 rpm were given and broken material was discarded. Weight the specimen without discarded material was noted. Cantabro loss was calculated based on the equation (3.9). For wet samples, samples were kept into the salty water for 24 hours (50gm salt into 1 liter) and rest procedure was similar to dry cantabro test. A maximum permissible value for dry samples was 15% and for wet samples 30% was taken.

$$CL = (A-B)/A*100 \quad (\text{Eq. 3.9})$$

Parameter used:

CL is the cantabro loss in %

A is the initial weight of test sample

B is the final weight of test sample



Figure 3. 16 : Loss Angles Abrasion Machine

3.1.5 Performance Test

Performance tests performed for design of porous asphalt mix under this project was permeability test, indirect tensile test, moisture susceptibility test, rutting, and dynamic creep test. Detail of each test is discussed below.

3.1.5.1 Permeability test (FM 5-565)

Permeability test was performed according to Florida method FM 5-565, to determine the infiltration rate of water through asphalt compacted individuals. In this test water from cylinder is allowed to pass from the compacted saturated specimen and the interval of time taken by water to reach the known head is recorded. The coefficient of permeability is determined based on Darcy law. This test is basically used for dense graded

mix, however if used for the open graded mix the flow may not be one dimensional and laminar, so it will affect the accuracy of the result.

A general procedure followed for permeability test was, sample dimension was noted at different location. Specimens were soaked in water for two hours, and mom rubber was pasted to side of the specimen so that water will not pass through the side of the samples. Air was evacuated from the sealing tube and sample was placed on the lower plate. Graduated cylinder was inserted on the upper cap and placed on the sample. Graduated cylinder was filled with water and membrane was inflated to 10psi throughout the test. Initial head of cylinder was noted and water was released from the cylinder till final head come. Time to reach from initial head to final head was noted and temperature at outlet of water also noted. This procedure was repeated thrice per specimen to take the median value of permeability. Permeability of samples was calculated by formula given below and minimum value of permeability should be 100m/day as per ASTM. All the apparatus used in permeability test and complete setup is shown in Figure 3.17 and 3.18 respectively.

The coefficient of the permeability, k is determined by equation (3.10).

$$k = \frac{aL}{At} * \ln\left(\frac{h1}{h2}\right) * tc \quad (\text{Eq. 3.10})$$

Parameter used:

k denotes, coefficient of permeability, cm/sec

a denotes, inside cross section area of the burette, cm²

L denotes, average thickness of the test specimen, cm

A denotes, average cross sectional area of the test specimen, cm²

t denotes, elapsed time between h1 and h2, sec

h1 denotes, initial head across the test specimen, cm

h2 denotes, final head across the head specimen

t_c denotes, temperature correction for the viscosity of the water , a temperature of 20C is used as the standard.



Sealing tube



Cylinder for filling water



Upper frame

Figure 3. 17 : Apparatus for Permeability Test



Figure 3. 18 : Permeability Test Setup

3.1.5.2 Indirect Tensile Strength (D 6931-12)

ITS was performed conducted according to test method IDT (D 6931-12), to calculate the strength of sample by applying a peak load .In this test cylindrical specimen was loaded from its vertical diameter plane at a specified rate of deformation as shown in Figure 3.19. The peak load was noted where failure occur and was used to find IDT. The IDT value was used to find out the quality of the bituminous mixture in respect with the cracking and rutting. Also the result was used to find out the moisture damage of the conditioned and unconditioned samples. IDT value can be calculated by equation (3.11).

$$S_t = (2000 * P) / (\pi * t * D) \quad (\text{Eq. 3.11})$$

Parameter used :

S_t denotes, IDT strength, kPa

P denotes, Maximum load, N

t denotes, Specimen height before test, mm

D denotes, Specimen diameter



Figure 3. 19 : Indirect Tensile Strength Machine

3.1.5.3 Moisture Induced Sensitivity Test (ASTM D7870/D7870-13)

MIST was performed according to ASTM D7870/D7870-13, to calculate the moisture damage of compacted asphalt samples (Figure 3.20). Moisture damage of road mainly depends on aggregates mineralogy, air voids, water, applied stress and the temperature. In this test actual condition was produced that road will face over time from traffic under normal temperature and wet condition. In this test samples were exposed to hydrostatic pressure in a closed chamber, with 3500 cycles, 40psi pressure and at 60 degree Celsius. After completing the number of cycles (took approximately 5 hours), samples was put into water bath for 2 hours at 25degree Celsius. After this samples were tested for ITS. Minimum value of moisture susceptibility should be at least 80% as per ASTM.



Figure 3. 20 : MIST Machine

3.1.5.4 Skid Resistance Measurement

Skid resistance is the resistance to the tire of vehicle when it is resisted to rotate along the pavement. Skid resistance is commonly measured as friction factor or skid number. Friction factor (coefficient of friction), μ , can be calculated using equation (3.12) Skid Numbers, higher the skid number better will be the road and is calculated using equation (3.13)

$$\mu = F / F_w \quad (\text{Eq. 3.12})$$

Parameter used:

F denotes, tangential friction force

F_w denotes, vertical load

$$\text{Skid number, SN} = 100 * \mu \quad (\text{Eq. 3.13})$$

British Pendulum Tester (BPT)

BPT is portable, can be carried out at the site or may be used in laboratory experiments as shown in Figure 3.21. BPT imitates the skid resistance given by a road surfaces to vehicle travelling at speed of 50 kmph. In this test two slabs was tested for skid resistance one porous slab and second dense slab. Slab was adjusted on balance surface along with British pendulum tester. A pendulum was moving in circular motion about a spindle which is attached to a pillar. A konown mass was attached to the arm which was rotating. When pendulum was released to move over the pavement, it travel a certain distance on pavement and this distance was noted as skid number on instrument.



Figure 3. 21 : British Pendulum Tester

3.1.5.5 Dynamic Creep Test DD (226:1996)

This test was conducted according to DD 226:1996, to determine permanent deformation of bituminous mixture at a particular temperature and load. This method determines the deformation of bituminous mixture which is similar to condition as experienced on roads.

In this method samples were conditioned for 4 hours at temperature $50 \pm 0.5^{\circ}\text{C}$. Samples were placed into the upper and lower platen and sensor was inserted. Some parameter were required to fill into the desktop such as diameter and height of the samples, 100kPa cyclic load stress, 30 kPa seating stress, 10kPa preload axial stress, 600sec preload time duration, 1800 maximum cycle count and 10% accumulated axial strain as shown in Figure 3.22.

Test was started after preload time displacement curve was obtained. It took 3600 second to complete the test and some samples were also failed before 3600 cycles. Figure 3.23 and Figure 3.24 complete setup of dynamic creep test and failed sample.

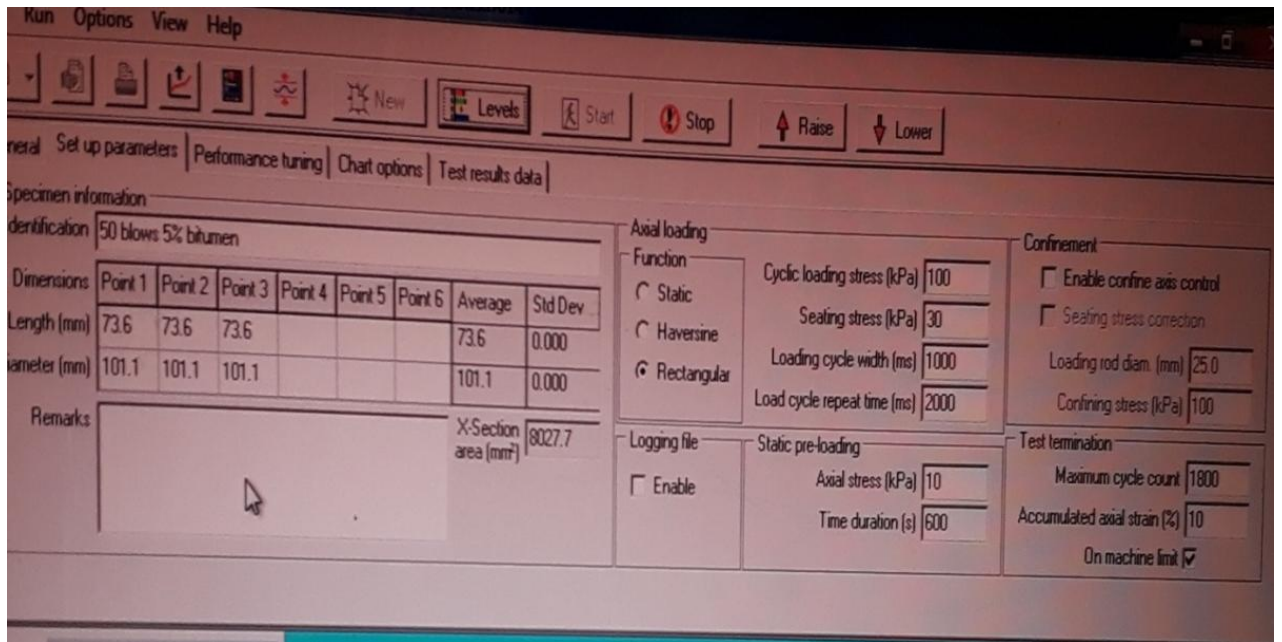


Figure 3. 22 : Input Parameter Screen



Figure 3. 23 : Complete Setup of Dynamic Creep Test



Figure 3. 24 : Failed Sample

3.1.5.6 Slab Casting

Slab was casted for rutting test and for demonstration of prototype. Slab may be casted by fixing number of blows or height of slab. Here the slab was casted by fixing height of slab and apparatus itself give number of passes to acquire the required air void content in the slab. Dimension of slab casted in this device was 41cm * 26 cm *5.3 cm.

Weight of aggregates taken 11033gm, weight of bitumen and fiber was taken as percentage by weight of aggregate. Total weight of mix was 11672.2gm. Density of aggregates at 5.5 % asphalt content by weight of aggregates with 40 blows of hammer was 2.07. Volume of slab was calculated as 5639.1cc and corresponding obtained height of slab was 5.3cm. Ingredients required for casting slab are shown in below Table 3.4.

By mixing the material as describe above at mixing temperature. Mixed material was transferred into the preheated mould by placing filter paper at bottom of mould and on top of slab. Other parameters such as height were fixed into the system provided with machine. Test was started and it was automatically stopped after a height of 5.3 cm was attained. After cooling the mould, slab was removed from the slab mould. Figure 3.25 and 3.26 shows slab casting machine and Figure 3.27. shows view of prepared slab.

Table 3. 4 : Material Used for Casting of Slab

Length of slab	cm	41
Width of slab	cm	26
Weight of aggregates	gm	11033
5.5% Bitumen content by weight of aggregates	gm	606.8
0.3% Fiber	gm	33.1
Total weight	gm	11672.9
Density of slab at 5.5% (40blows of hammer)	gm/cc	2.1
Volume of slab	cc	5639.1
Height of slab	cm	5.3



Figure 3. 25 : Inside View of Slab Casting Machine



Figure 3. 26 : Front View of Slab Casting Machine



Z

Figure 3. 27 : Prepared Slab

Core cutting: Core was also cut from the prepared slab, to determine air void content in the slab and to check the permeability of slab. Figure 3.28 Shows view of core cutting from prepared slab for testing purpose.

Slab Cutting: Slab prepared by above procedure was cut for demonstration of prototype and rutting test. Slab was cut by saw cutter in a dimension of 36cm * 25cm * 5.3cm and 30cm * 30cm * 5cm for prototype and rutting test respectively. The saw cutter is shown in Figure 3.29 and 3.30.



Figure 3. 28 : Core Cutting Machine



Figure 3. 29 : Front View of Saw Cutter



Figure 3. 30 : Side View of Saw Cutter

3.2 FILTER LAYER GRADATION

Filter layer was designed as per AASHTO No. 57, containing maximum 37.5mm size aggregates as shown in Table 3.5. This layer lies between surface layer and the reservoir layer are, void content in this layer should be 40% (maximum). Figure 3.31 shows selected gradation for choker course layer.

Table 3. 5 : Selected Gradation for Filter Layer

Sieve (mm)	% Passing			% Retained
	Lower Limit	Upper Limit	Selected Gradation	
37.5	100	100	100	0
25	95	100	97.5	2.5
19	25	60	42.5	55
4.75	0	10	5	37.5
2.36	0	5	2.5	2.5
pan				2.5

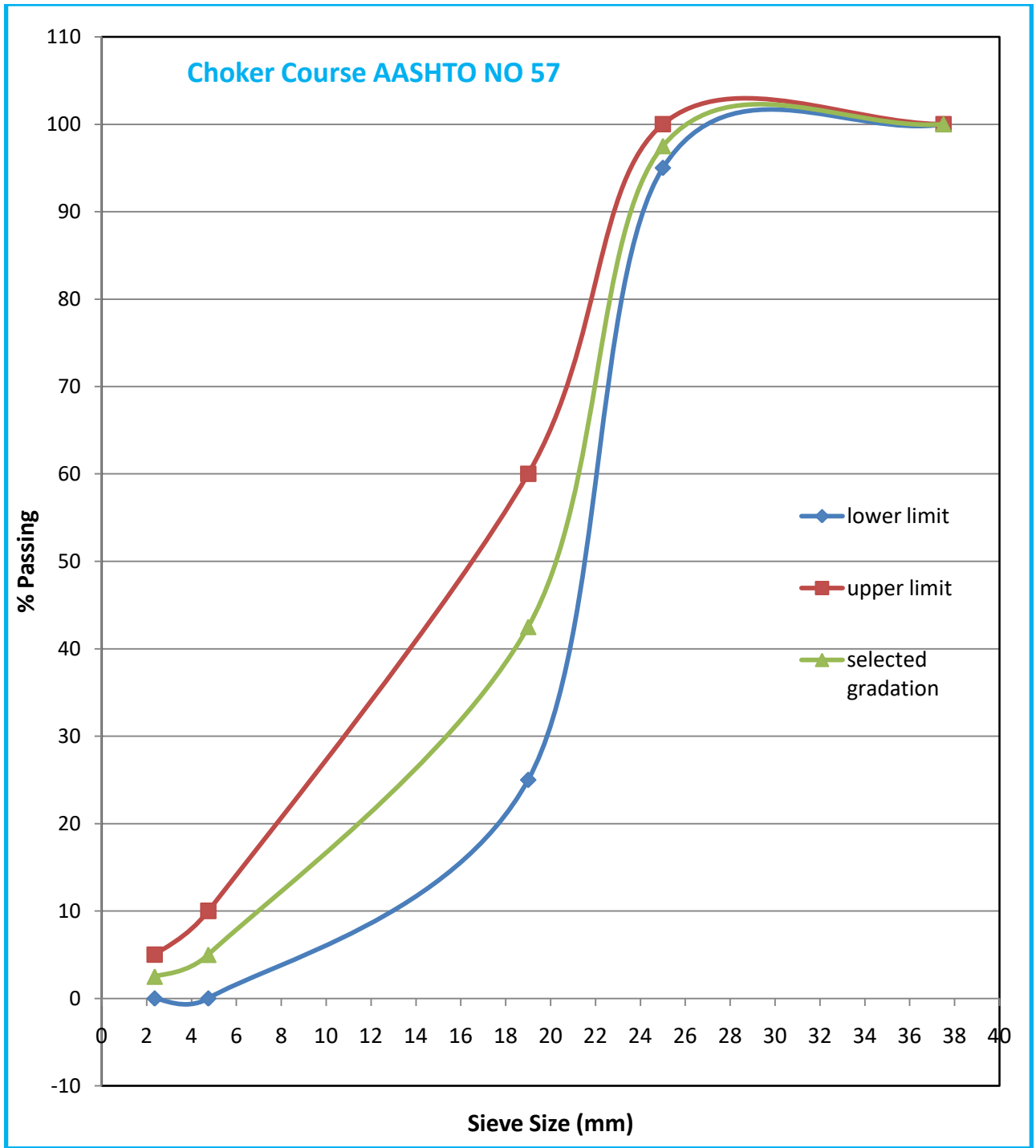


Figure 3. 31 : Selected Gradation for Choker Course

3.3 RESERVOIR LAYER GRADATION

Reservoir layer was the last layer in the design of permeable bitumen pavement. This layer was designed for storing water temporary, for this purpose void content in reservoir layer was (minimum) 40%. AASHTO No. 3 gradation was used to design the reservoir layer as shown in Table No. 3.6. Figure 3.32. Shows selected gradation for reservoir layer.

Table 3. 6 : Selected Gradation for Reservoir Layer

Sieve (mm)	% Passing			% Retained
	Lower Limit	Upper Limit	Selected Gradation	
63	100	100	100	0
50	90	100	95	5
37.5	35	70	52.5	42.5
25	0	15	7.5	45
12.5	0	5	2.5	5

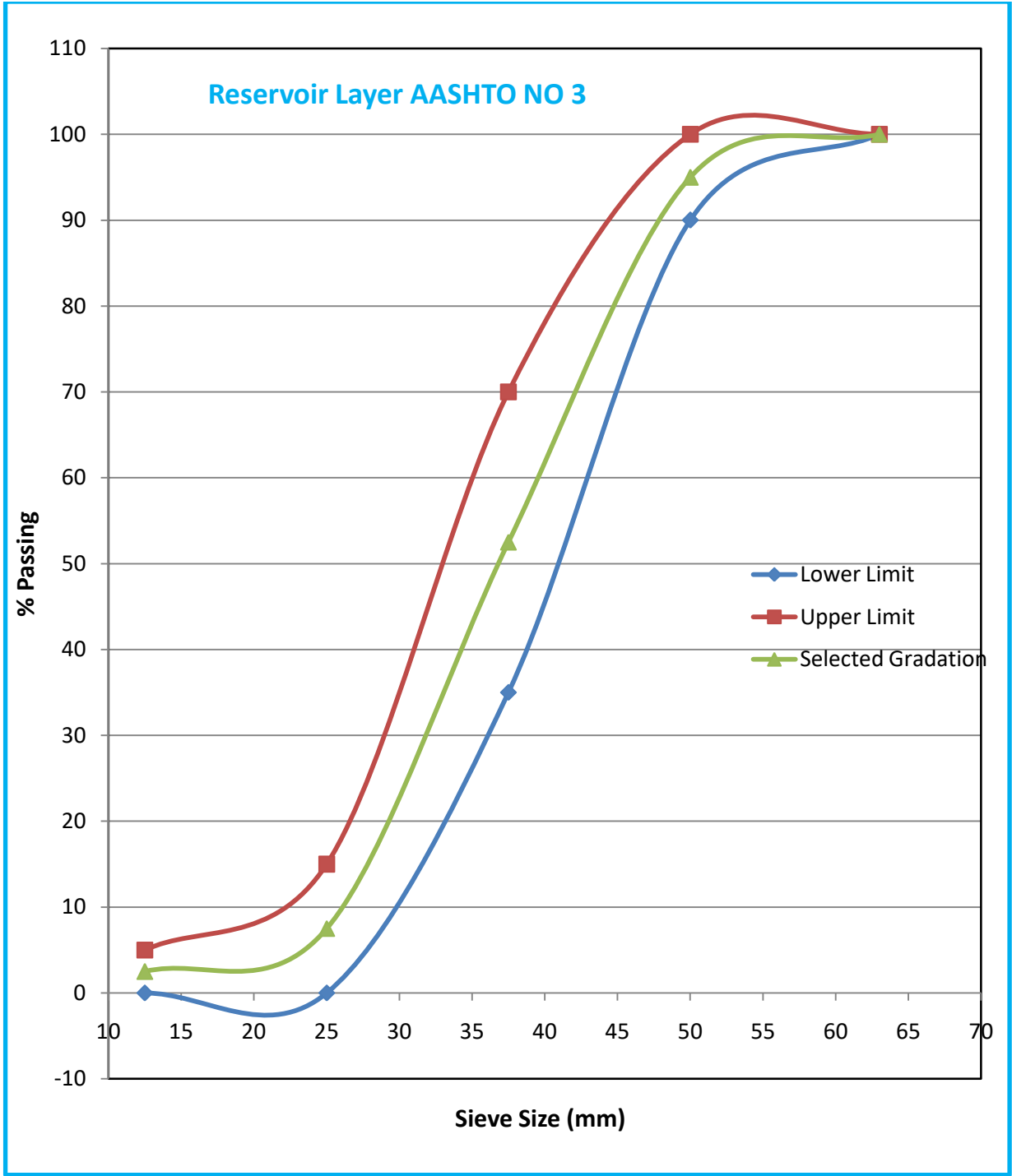


Figure 3. 32 : Selected Gradation for Reservoir Layer

CHAPTER 4 RESULT AND DISCUSSION

Results and observations of all the tests are explained here. The material test result (viz. aggregate tests, bitumen tests), tests for optimization of bitumen content have been presented in this chapter like bulk specific gravity, maximum specific gravity, air voids content, drain-down test, cantabro test for dry and wet samples, and performance test like permeability test, indirect tensile test, moisture susceptibility test, skid resistance and dynamic creep test are presented and explained in this chapter.

4.1 AGGREGATE TESTING RESULT

Aggregate tests which were performed include, impact test, combined flakiness and elongation indices test, specific gravity and water aggregate absorption test, abrasion test and stripping value test. All the properties of aggregate are within the specified limit as per requirement. Therefore the tested aggregates can further be used for mix design. All the test values of aggregates are shown in Table 4.1.

Table 4. 1 : Physical Property of Aggregates

Tests	For 10mm aggregates	For 20mm aggregates	Permissible value as per MORTH 2013	IS code
Aggregate Impact test	18.8%	19.6%	Less than 30%	2386-iv
Combined Flakiness and Elongation Indices	27.34%	26%	Less than 35%	2386-i
Specific gravity(for aggregate mix)	2.66		Between 2.5 to 3.2	2386- iii
Water absorption (for aggregate mix)	0.52		Between 1 to 2%	2386- iii
Abrasion test	26.08%		Less than 30%	2386-iv
Stripping value test	nil		Less than 5%	6241-1971

4.2 BITUMEN TESTING RESULT

The various test performed on the collected bitumen sample proposed to be used under this project were penetration test, ductility test, viscosity test and softening point test. All the properties of bitumen are within the specified limit as per requirement. So the tested asphalt can further be used for mix design. All test values of bitumen are shown in Table 4.2.

Table 4. 2 : Bitumen Properties as Observed in the Laboratory

Tests	Test value	Minimum value As per IS:73-2013	IS code used
Penetration at 25 ⁰ C, 100gm, 5sec, 0.1mm	51.3	45	1203-1978
Softening Point (R & B) ⁰ C	55	47	1205-1978
Kinematic Viscosity at 135 ⁰ C, cst	519.8	350	1206-1978
Ductility at 27 ⁰ C	75	40	1208-1978

4.3 STONE-TO-STONE CONTACT CRITERIA

Gradation used for design of surface layer of porous asphalt pavement fulfills ASTM, NAPA, NCAT & UNHC standards. Gradation should ensure stone-to-stone contact, for this purpose $VCA_{MIX} < VCA_{DRY}$. VCA_{mix} at three binder 5%, 5.5% and 6% are shown in Table 4.3.

In VCA_{DRC} , γ_s was calculated based on test method C29/C29M method. In this test a cylinder of capacity 14.28 liter was filled with coarse aggregates in three layers, tamping every layer 25 times. Aggregate weight filled into cylindrical mould was taken and unit weight of coarse aggregates was calculated by, weight of coarse aggregates divided by volume cylinder.

$$VCA_{MIX} < VCA_{DRY}$$

Table 4. 3 : Void in Coarse Aggregate Mix for Surface Layer

Bitumen Content %	Number of blows	VCAmix = 100 - Gmb*Pca/Gca
5.0	30	37.70
	40	35.83
	50	35.00
5.5	30	36.78
	40	35.52
	50	35.20
6	30	36.68
	40	34.56
	50	34.44

VCA_{DRC}, Void in coarse aggregates (dry rodded condition) was calculated as shown in Table 4.4.

Table 4. 4 : VCA(Dry Rodded Condition) for Surafce Layer

The weight of compacted aggregate	Volume of mould	The bulk density of aggregates (γ_s)	Bulk sp. Gr. of coarse aggregates (G_{CA})	Dry aggregate air voids (VCA_{DRY})
Kg	L	Kg/m³		%
23.76	14.24	1668.5	2.76	39.4

Since $VCA_{MIX} < VCA_{DRY}$ at all binder content. This ensures stone to stone contact of aggregates.

4.4 AIR VOIDS CONTENT RESULT

Air voids were dependent on two parameters; maximum specific gravity of loose mix samples and bulk specific gravity of compacted asphalt samples. Result from both the test is shown in below tables.

4.4.1 Maximum Specific Gravity (Gmm)

It was calculated at 5% bitumen content of total aggregates. Average of three samples was taken and value of maximum specific gravity calculated was 2.75 as shown in Table 4.5. Maximum specific gravity at other binder content 5.5% and 6% was calculated by back calculation and value found was 2.53 and 2.51 as shown in Table 4.6.

Table 4. 5 : Gmm by Rice Apparatus

Bitumen content	Weight of dry specimen in air (A)	Weight of bucket filled with water and aggregate	Weight of bucket filled with water	Submerged weight of sample in water (C)	Theoretical maximum specific gravity, Gmm = A/A-C	Average value
%	Gm	gm	gm	gm		
5	1260.5	8224	7459.5	764.5	2.54	2.55
	1266	8229	7459.5	769.5	2.55	
	1235	8210.5	7459.5	751	2.55	

Table 4. 6 : Maximum Specific Gravity (Gmm) by the Back Calculation

Aggr egate	Binder	Fibe r	Total weight	% of Aggreg ate by total mix (Ps)	% of binder by total mix weight (Pb)	Maximum gravity (Gmm)	Specific gravity of binder (Gb)	(Effective specific gravity of mix)Gse= Ps/(100/G mm)-(Pb- Gb)
gm	gm	gm	gm	%	%			
1200	60(5%)	3.6	1263.6	94.97	4.75	2.55	1.01	2.75
1200	66(5.5%)	3.6	1269.6	94.52	5.20	2.53	1.01	
1200	72(6%)	3.6	1275.6	94.07	5.64	2.51	1.01	

4.4.2 Bulk Specific Gravity (Gmb)

Bulk specific gravity of compacted asphalt samples was calculated at 5%, 5.5% and 6%, at 30, 40 and 50 blows, average of three samples was taken. Here bulk specific gravity was calculated by software Gravity Suite. Bulk specific gravity at each bitumen content 5%, 5.5% and 6% by weight of aggregates is shown in Table 4.7. At 5% bitumen content of total aggregates, the air void criteria of 18% were satisfied at each blows of marshal hammer. At 5.5% bitumen content of total aggregates, air voids criteria of 18% was satisfied at only 30 and 40 blows of marshal hammer. At 6% bitumen content of total aggregates, air voids criteria of 18% was satisfied at only 30 blows of marshal hammer.

Table 4. 7 : Bulk Specific Gravity (Gmb) by Core Lok Apparatus

Bitumen content	Number of blows	Sample ID	Bag Weight	Sample Weight before Sealing	Sealed Sample Weight in Water	Sample Weight after Water Submersion	Density of Water for temperature correction	Maximum Specific Gravity	Bulk Specific Gravity	Air Voids	Average bulk specific gravity	Average air voids
%			gm	gm	gm	gm	gm/cm ³			%		
5	30	1	26.6	1240.5	614.3	1240.5	1	2.55	2.00	21.40	2.00	21.54
		2	26.4	1258.9	621.4	1258.9	1	2.55	2.00	21.67		
	40	4	26.6	1263.9	637.3	1263.7	1	2.55	2.04	19.94	2.06	19.18
		5	26.4	1256.3	645.2	1256.3	1	2.55	2.08	18.42		
	50	7	26.1	1263.2	656.1	1263.1	1	2.55	2.11	17.42	2.09	18.14
		8	26.4	1249.7	638.1	1249.3	1	2.55	2.07	18.86		
5.5	30	10	26.2	1258.7	632.6	1258.6	1	2.53	2.03	19.60	2.03	19.74
		11	26.4	1245.1	623.6	1245	1	2.53	2.03	19.87		
	40	16	26.6	1255.9	639.7	1256.1	1	2.53	2.06	18.51	2.07	18.14
		17	26.4	1261.8	648	1261.8	1	2.53	2.08	17.78		
	50	13	26.3	1250.5	639.7	1250.7	1	2.53	2.07	18.14	2.08	17.73
		14	26.4	1262.7	651.7	1262.6	1	2.53	2.09	17.32		
6	30	19	26.4	1241.5	622.3	1241.5	1	2.51	2.03	19.18	2.03	18.98
		20	26.4	1252	630.6	1252	1	2.51	2.04	18.79		
	40	22	26.6	1257.5	650.1	1257.5	1	2.51	2.10	16.52	2.10	16.26
		23	26.3	1263.3	656.7	1263.1	1	2.51	2.11	16.00		
	50	25	26.3	1271.4	666	1271.3	1	2.51	2.13	15.31	2.11	16.11
		26	26.3	1257	647.1	1257	1	2.51	2.09	16.91		

From the result of core lok test a given in Table 4.7, Table 4.8 has been prepared which shows specific gravity v/s average air voids for different binder content at 30, 40 and 50 blows.

Table 4. 8 : Bitumen Content v/s Air void content

Bitumen content in %	Number of blows	Average specific gravity	Average air voids (%)
5	30	2.00	21.54
	40	2.06	19.18
	50	2.09	18.14
5.5	30	2.03	19.74
	40	2.07	18.14
	50	2.08	17.73
6	30	2.03	18.98
	40	2.10	16.26
	50	2.11	16.11

Figure 4.1 shows air void content versus asphalt content. This graph represents that air void content decreases with increase in asphalt content. At 30 blows of marshal hammer air void content was very high and decreases as number of blows increases

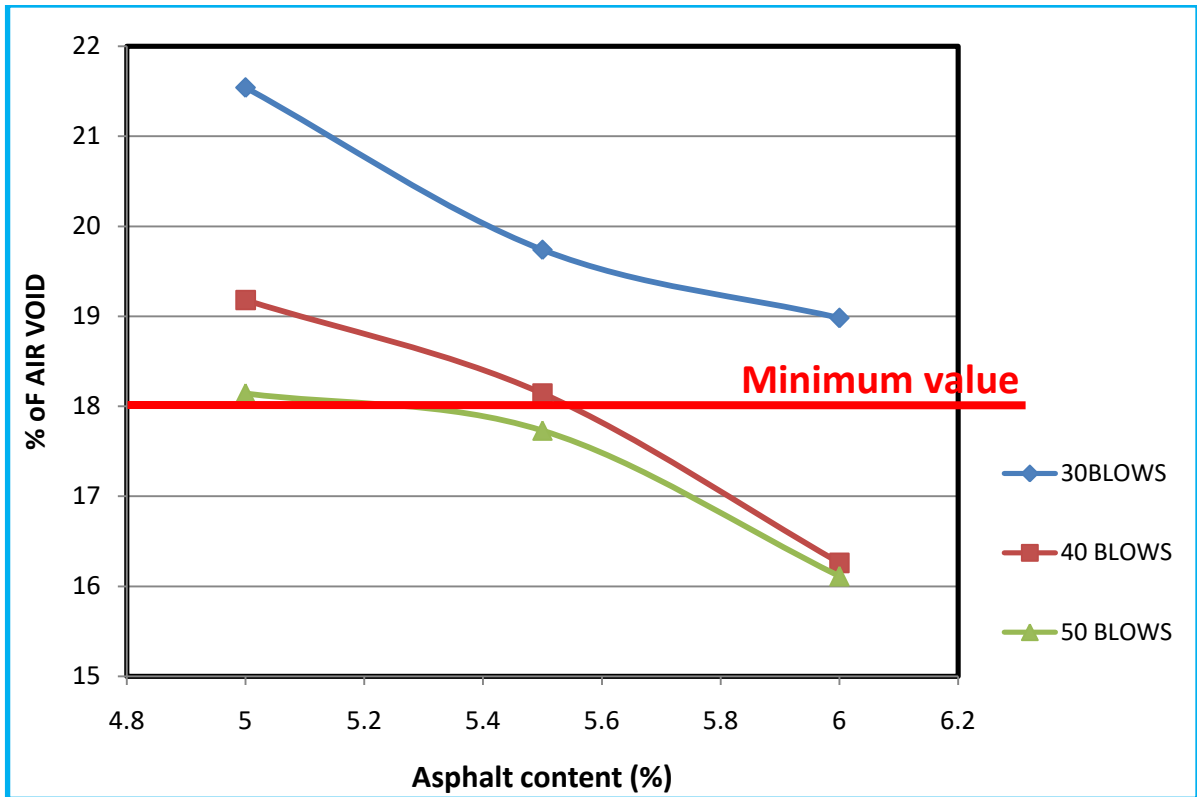


Figure 4. 1 : Asphalt Content v/s Air Void

4.4.3 VMA and VFA Result

VMA is expressed as percentage of total volume or it can be defined as the void in aggregate in compacted form without adding asphalt.

VMA was calculated by equation (4.1)

$$\text{VMA} = 100 - G_{mb} * \frac{P_s}{G_{sb}} \quad (\text{Eq. 4.1})$$

Parameters used in equation 4.1 are:

G_{mb} is the bulk specific gravity

P_s is the % of aggregate by total mix

G_{sb} is the bulk specific gravity

VFA (void filled with asphalt) is defined as that percentage by volume of VMA that is filled with effective binder.

VFA can be calculated by equation (4.2).

$$VFA = 100 * (VMA - P_a) / VMA \quad (\text{Eq. 4.2})$$

Where

VMA = Void filled with asphalt

P_a = air void in compacted mixture, percentage by total volume

Table 4.9 shows the VMA and VFA at 5%, 5.5% and 6% bitumen content of total aggregates. From the Table 4.9 it is clear that at same bitumen content with increase in compactive effort, air void content and VMA decreases.

Table 4. 9 : VMA AND VFA

Bitumen content in %	Number of blows	Bulk Specific Gravity (Gmb)	Average specific gravity	% of Aggregate by total mix (Ps)	The bulk specific gravity of aggregate Gsb	% Air Voids	% of average air voids	VMA voids in mineral aggregate	VFA void filled with asphalt
5	30	2.00	2.00	94.97	2.66	21.40	21.54	28.57	24.61
		2.00				21.67			
	40	2.04	2.06	94.97	2.66	19.94	19.18	26.42	27.41
		2.08				18.42			
	50	2.11	2.09	94.97	2.66	17.42	18.14	25.47	28.80
		2.07				18.86			
5.5	30	2.03	2.03	94.52	2.66	19.60	19.74	27.85	29.12
		2.03				19.87			
	40	2.06	2.07	94.52	2.66	18.51	18.14	26.41	31.31
		2.08				17.78			
	50	2.07	2.08	94.52	2.66	18.14	17.73	26.04	31.91
		2.09				17.32			
6	30	2.03	2.03	94.07	2.66	19.18	18.98	28.08	32.40
		2.04				18.79			
	40	2.10	2.10	94.07	2.66	16.52	16.26	25.67	36.64
		2.11				16.00			
	50	2.13	2.11	94.07	2.66	15.31	16.11	25.53	36.91
		2.09				16.91			

From the test results given in Table 4.9, Table 4.10 has been prepared which shows summary of VMA and VFA for different bitumen content and marshal blows.

Table 4. 10 : Summary of VMA and VFA

Bitumen content in %	Number of blows	VMA (voids in mineral aggregate)	VFA (void filled with asphalt)	% of average air voids
5	30	28.57	24.61	21.54
5.5	30	27.85	29.12	19.74
6	30	28.08	32.40	18.98
5	40	26.42	27.41	19.18
5.5	40	26.41	31.31	18.14
6	40	25.67	36.64	16.26
5	50	25.47	28.80	18.14
5.5	50	26.04	31.91	17.73
6	50	25.53	36.91	16.11

4.5 DRAIN-DOWN TEST RESULT

Drain-down test was conducted at three bitumen content 5%, 5.5% and 6% by weight of total aggregates, pellet fiber was also added to it 0.3% by weight of aggregates. Table 4.11 and Figure 4.2 shows the result obtained from drain-down test, drain-down value at 5% and 5.5% bitumen content was observe zero and at 6% bitumen content drain-down value was 0.04. Drain-down value shows that it increases with increase in bitumen content, but the drain-down at each bitumen content was less than maximum permissible value of 0.3%. So it is suggested that mixture is passed in this test.

Table 4. 11 : Draindown Test Result

Bitumen content	The final weight of the plate (A)	The initial weight of the plate (B)	Initial total sample weight (C)	Drain-down value
%	gm	gm	gm	%
5	235	235	1249.5	0
5.5	235	235	1271	0
6	235.5	235	1232.5	0.04

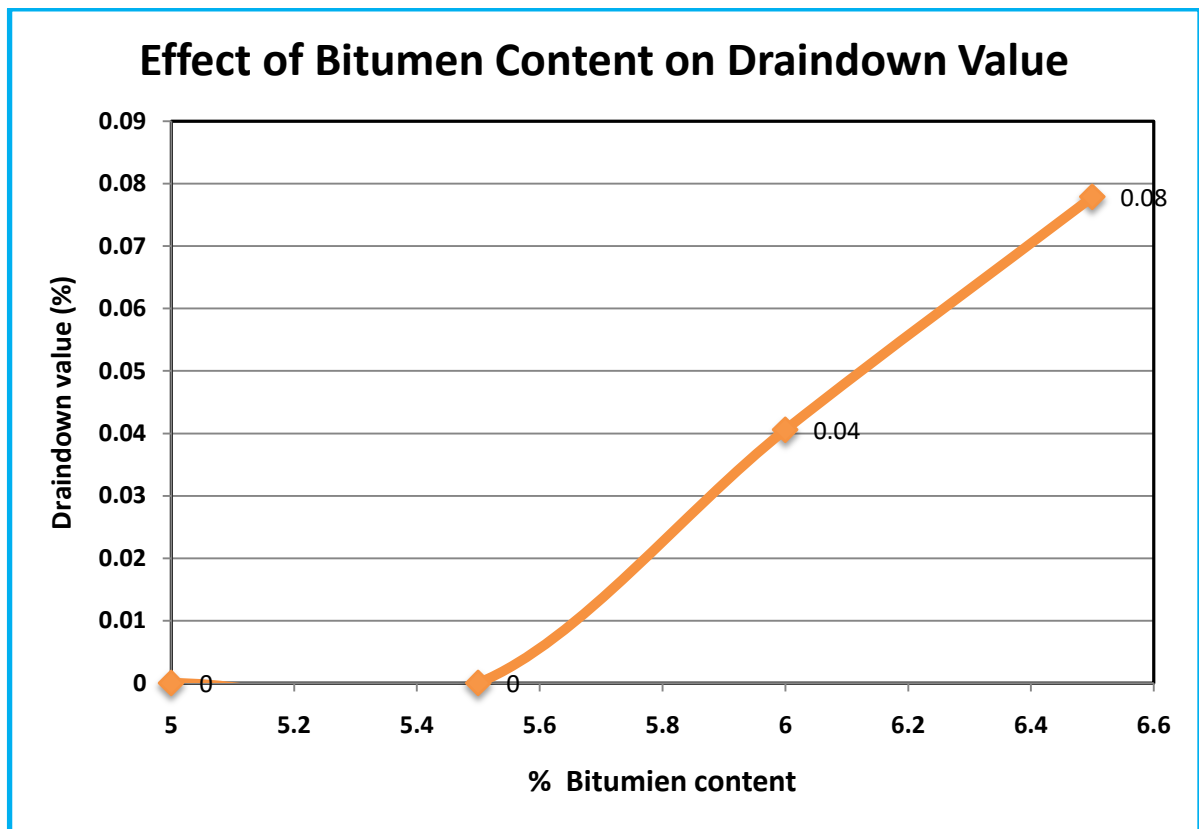


Figure 4. 2 : Bitumen Content Versus Draindown Value

4.6 CANTABRO TEST RESULT

Cantabro test was performed at three binder content 5%, 5.5% and 6%, with different number of blows 30, 40 and 50. This test was performed on both wet and dry conditioned. Table 4.12 and Figure 4.3 shows result form cantabro test with dry specimen and and Table 4.13 and Figure 4.4 shows result from cantabro test with wet specimen.

From the dry cantabro test observation it is clear that cantabro loss decreases with increase in number of marshal blows. With increase in bitumen content cantabro loss also decreases. It is clear from the observation that cantabro loss depend on bitumen content and compactive effort. This condition also valid for wet conditioned cantabro test, but after wet conditioning, cantabro loss increases with more percentage.

Table 4. 12 : Cantabro Test Result on Dry Specimen

Bitumen content	Sample number	Number of blows given to the sample	Initial weight of test specimen (A)	Final weight of specimen (B)	Cantabro loss =(A-B)/A*100
%			gm	gm	%
5	3	30	1262.5	1123.5	11.01
	6	40	1259	1148	8.82
	9	50	1166.5	1108.5	4.97
5.5	12	30	1248.5	1132.5	9.29
	15	40	1257.5	1135.5	9.70
	18	50	1265	1158.5	8.42
6	21	30	1261	1173	6.98
	24	40	1257.5	1172	6.80
	27	50	1259.5	1195.5	5.08

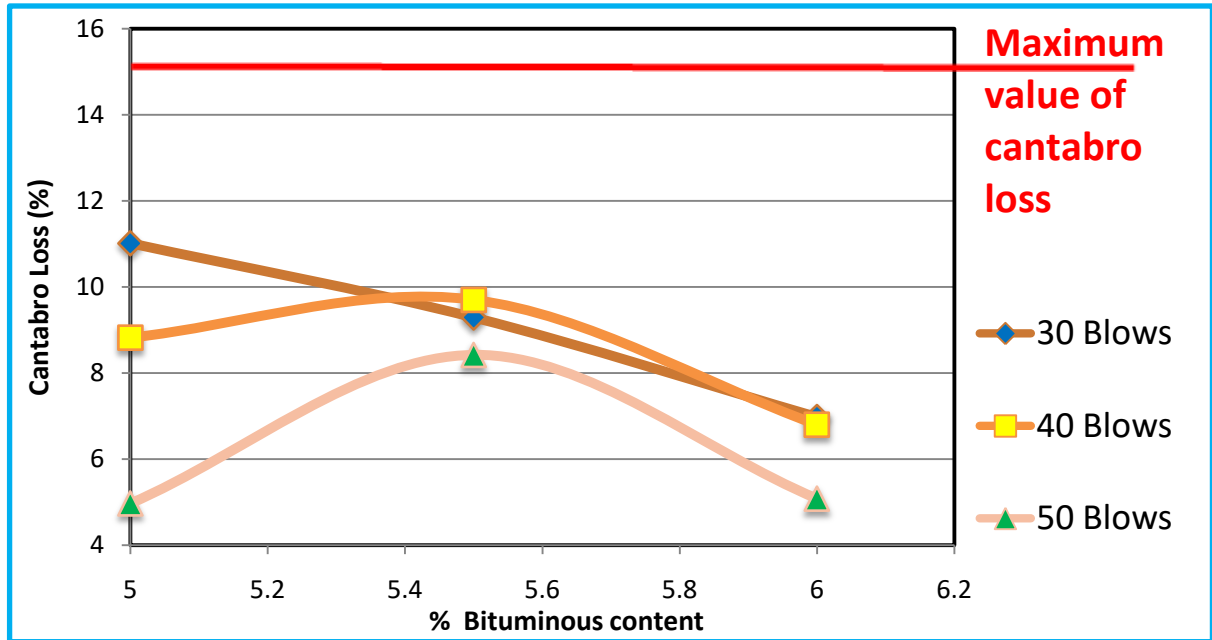


Figure 4. 3 : Bitumen Content Versus Cantabro Loss on Dry Specimen

Table 4. 13 : Cantabro Test Result on Wet Specimen

Bitumen content	Sample number	Number of blows given to	Initial weight of test specimen (A)	Final weight of test specimen B	Cantabro loss $= (A-B)/A * 100$
%			gm	gm	%
5	1	30	1283.5	786	38.76
	4	40	1276	870	31.82
	7	50	1298	896	30.97
5.5	10	30	1290	884	31.47
	17	40	1297.5	910	29.87
	14	50	1295	925	28.57
6	19	30	1286	890	30.79
	22	40	1283.5	949	26.06
	26	50	1279	1022	20.09

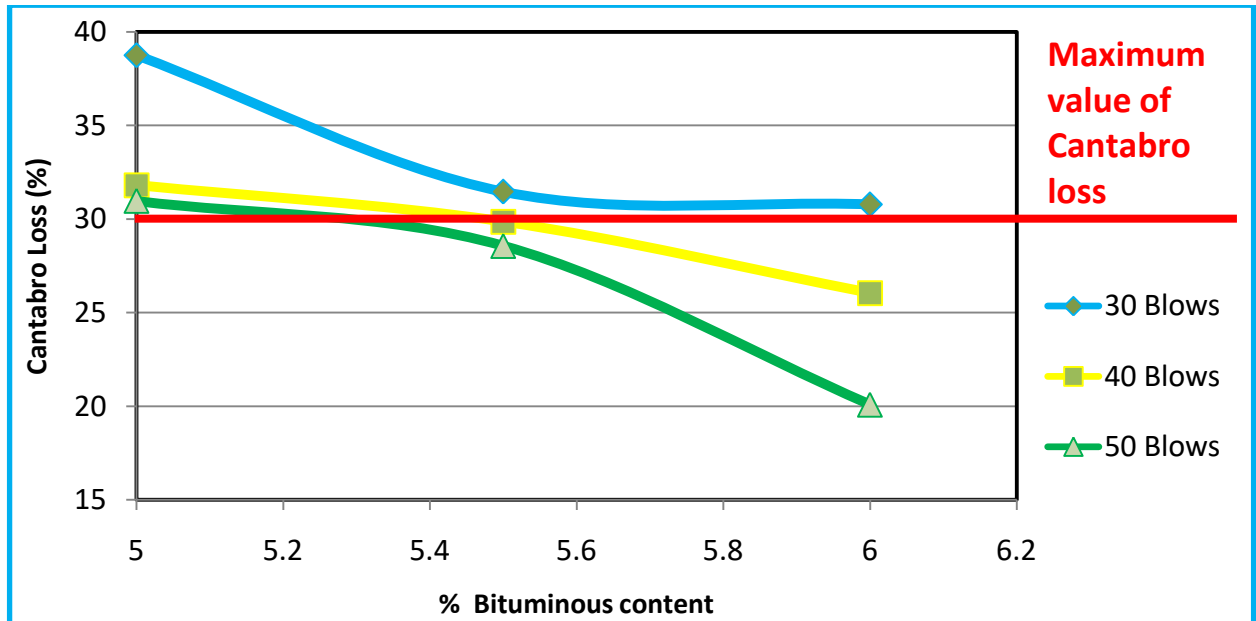


Figure 4. 4 : Bitumen Content Versus Cantabro Loss on Wet Specimen

4.7 OPTIMUM BITUMEN CONTENT

Optimum bitumen content was chosen according to three conditions viz. air void criteria, draindown test & the cantabro test with dry & wet specimen. The air void is the key factor around which the porous pavement design revolves. The minimum air void should be 18% in the surface layer. The sample was prepared at 5%, 5.5% and 6% binder content at 30, 40 and 50 blows. The test result showed that at 5 % bitumen content air void criteria was satisfied, at 5.5% bitumen content 30 blows and 40 blows specimen satisfied the air void criteria and at 6% bitumen content only 30 blows specimen satisfies the air void criteria.

The drain down test was done to check the draining of bitumen from the mix and for this 0.3% fiber by weight of aggregates was added to the bituminous mixes having 5%, 5.5% and 6% binder content. The result of drain-down test shows satisfactory result at each bitumen contents.

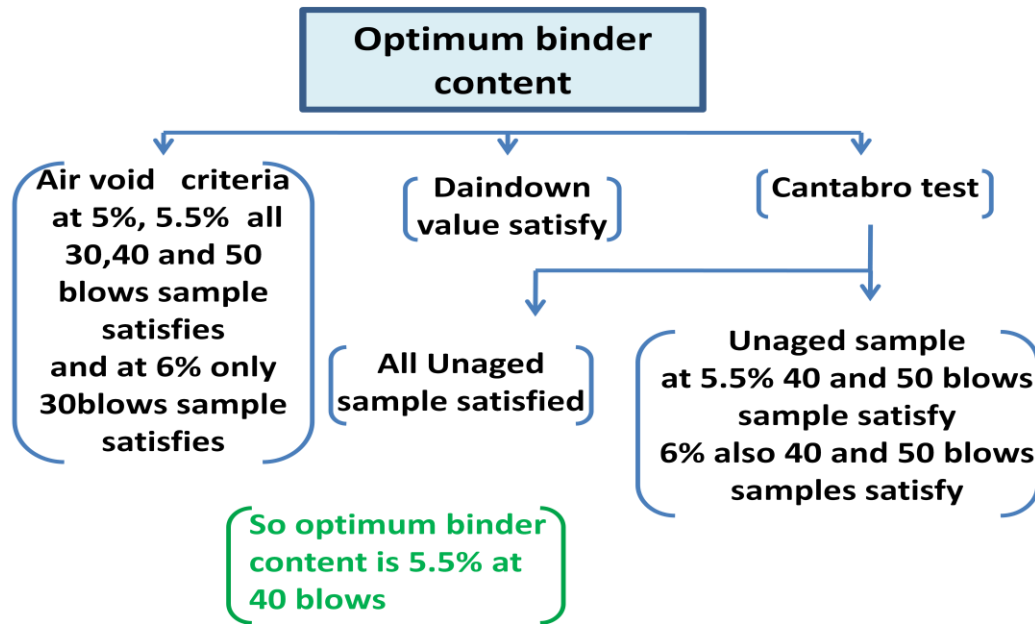
The third test for deciding optimum binder content was cantabro testing which shows the abrasion loss of the sample under the dry and wet condition. Under the dry condition all

prepared samples at each binder content were directly tested and it was found that cantabro loss criteria of 15% maximum loss were satisfied at each bitumen content. For wet specimen in salty water for 24 hours the maximum cantabro loss was 30% and which was satisfied at only 40 and 50 blows of 5.5% and 6% bitumen content.

The optimum binder of desired mix has been chosen as 5.5% by weight total aggregates at 40 blows, because at 5% bitumen content samples failed in cantabro aged test and at 6% bitumen content the air void criteria was not fulfilled. Table 4.14 shows summary of all the tests result to decide optimum binder content for selected porous asphalt pavement.

Table 4. 14 : Summary of All the Test Results to Decide Optimum Binder Content

Bitumen content	Number of blows	Average bulk specific gravity	% of average air voids	Drain-down value	Cantabro loss = $(A-B)/A*100$ unaged	Cantabro loss = $(A-B)/A*100$ aged
%			%	%	%	%
5	30 blows	2.00	21.54	0	11	38.76
	40 blows	2.06	19.18		8.81	31.81
	50 blows	2.09	18.14		4.97	30.97
5.5	30 blows	2.03	19.74	0	9.29	31.47
	40 blows	2.07	18.14		9.7	29.86
	50 blows	2.08	17.73		8.41	28.57
6	30 blows	2.03	18.98	0.04	6.97	30.79
	40 blows	2.10	16.26		6.79	26.06
	50 blows	2.11	16.11		5.08	20.09



Result: optimum binder content is 5.5% at 40 blows.

4.8 PERMEABILITY TEST RESULT

Permeability test was carried out at 5%, 5.5% and 6% bitumen content by weight of total aggregates, with 30, 40 and 50 blows of hammer. At each blows average of three specimens was taken. Observation form permeability test is presented in Table 4.15, Table 4.16 and Table 4.17 at 5%, 5.5% and 6% bitumen content by weight of aggregates respectively. The minimum recommended permeability value is 100m/day.

At 5% and 5.5% bitumen content by weight of aggregates, samples prepared at 30 and 40 blows of hammer satisfied the condition of permeability test, but at 6% bitumen content by weight of aggregates only samples prepared at 30 blows of hammer satisfied the criteria of permeability.

The test values show that with increase in number of blows at same bitumen content, permeability of sample decreases. Permeability of sample depends on air void content, air void decrease with increase in number of blows. So permeability and air void are directly proportional.

It was also observed that with increase in bitumen content at same number of blows, permeability of sample decreases. It is concluded that permeability of sample depends upon bitumen content and number of blows given to the sample. Figure 4.5 shows the permeability values above explained effect of bitumen content and number of blows. Table 4.18 shows summary of permeability test at different binder content.

Table 4. 15 : Permeability Test Result at Bitumen Content 5%

Sample ID	No. of blows	Dia. of sample	Average thickness of test specimen, (L)	Inside C/S area of buret, (a)	Average C/S area of test specimen, (A)	Elapsed time between h1 and h2, (t)	Initial head, (h1)	Final head, (h2)	Measured temp. at outlet	Temp. correction for viscosity of water (tc)	Coefficient of permeability, (k)	Average permeability	Permeability
		cm	Cm	cm ²	cm ²	sec	cm	cm	degree Celsius		cm/sec	cm/sec	m/day
1	30	10.13	7.52	7.91	80.55	6.2	76.4	15.4	21.2	0.97	0.185	0.184	159.3
1	30	10.13	7.52	7.91	80.55	6.28	76.4	15.4	20.8	0.98	0.185		
1	30	10.13	7.52	7.91	80.55	6.31	76.4	15.4	20.8	0.98	0.184		
4	40	10	7.5	7.91	78.5	8.41	76.4	15.4	22.2	0.95	0.137	0.138	119.2
4	40	10	7.5	7.91	78.5	8.5	76.4	15.4	22.4	0.94	0.134		
4	40	10	7.5	7.91	78.5	7.76	76.4	15.4	23.5	0.92	0.144		
7	50	10	7.43	7.91	78.5	23.4	76.4	15.4	23.6	0.92	0.047	0.047	40.1
7	50	10	7.43	7.91	78.5	23.8	76.4	15.4	23.8	0.91	0.046		
7	50	10	7.43	7.91	78.5	23.7	76.4	15.4	23.5	0.92	0.047		

Table 4. 16 : Permeability Test Result at Bitumen Content 5.5%

Sample ID	No. of blows	Dia. of sample	Average thickness of test specimen, (L)	Inside C/S area of buret, (a)	Average C/S area of test specimen, (A)	Elapsed time between h1 and h2, (t)	Initial head, (h1)	Final head, (h2)	Measured temp. at outlet	Temp. correction for viscosity of water (tc)	Coefficient of permeability, (k)	Average permeability	Permeability
		cm	Cm	cm ²	cm ²	sec	cm	cm	degree Celsius		cm/sec	cm/sec	m/day
10	30	10.06	7.76	7.91	79.445	8.4	76.4	15.4	22.8	0.94	0.138	0.135	116.4
10	30	10.06	7.76	7.91	79.445	8.69	76.4	15.4	22.9	0.93	0.132		
10	30	10.06	7.76	7.91	79.445	8.72	76.4	15.4	22.5	0.94	0.133		
17R	40	9.96	7.66	7.91	77.873	9.46	76.4	15.4	22.4	0.94	0.124	0.121	104.8
17R	40	9.96	7.66	7.91	77.873	10.5	76.4	15.4	22.1	0.95	0.113		
17R	40	9.96	7.66	7.91	77.873	9.2	76.4	15.4	22.5	0.94	0.127		
14R	50	10.16	7.56	7.91	81.032	17.56	76.4	15.4	22.2	0.95	0.064	0.064	54.9
14R	50	10.16	7.56	7.91	81.032	17.6	76.4	15.4	22.4	0.94	0.063		
14R	50	10.16	7.56	7.91	81.032	17.8	76.4	15.4	21.9	0.96	0.064		

Table 4. 17 : Permeability Test Result at Bitumen Content 6%

Sample ID	No. of blows	Dia. of sample	Average thickness of test specimen, (L)	Inside C/S area of buret, (a)	Average C/S area of test specimen, (A)	Elapsed time between h1 and h2, (t)	Initial head, (h1)	Final head, (h2)	Measured temp. at outlet	Temp. correction for viscosity of water (tc)	Coefficient of permeability, (k)	Average permeability	Permeability
			cm	cm ²	cm ²	sec	cm	cm	degree Celsius		cm/sec	cm/sec	m/day
19	30	10.1	7.7	7.91	80.078	7.43	76.4	15.4	22.2	0.95	0.156	0.158	136.0
19	30	10	7.8	7.91	78.500	7.29	76.4	15.4	21.9	0.96	0.166		
19	30	10.2	7.6	7.91	81.671	7.34	76.4	15.4	22.6	0.94	0.151		
23R	40	10	7.53	7.91	78.500	20	76.4	15.4	22.7	0.94	0.057	0.057	48.8
23R	40	10	7.53	7.91	78.500	20.14	76.4	15.4	22.8	0.94	0.057		
23R	40	10	7.53	7.91	78.500	20.5	76.4	15.4	22.5	0.94	0.056		
26	50	10.16	7.47	7.91	81.032	25.2	76.4	15.4	22.5	0.94	0.044	0.044	37.7
26	50	10.16	7.47	7.91	81.032	24.8	76.4	15.4	22.4	0.94	0.044		
26	50	10.16	7.47	7.91	81.032	25.4	76.4	15.4	22.6	0.94	0.043		

Table 4. 18 : Summary of Permeability Test Result at Three Bitumen Content

Bitumen content	Number of blows	Permeability
%		m/day
5	30	159.3
	40	119.2
	50	40.1
5.5	30	116.4
	40	104.8
	50	54.9
6	30	77
	40	48.8
	50	37.7

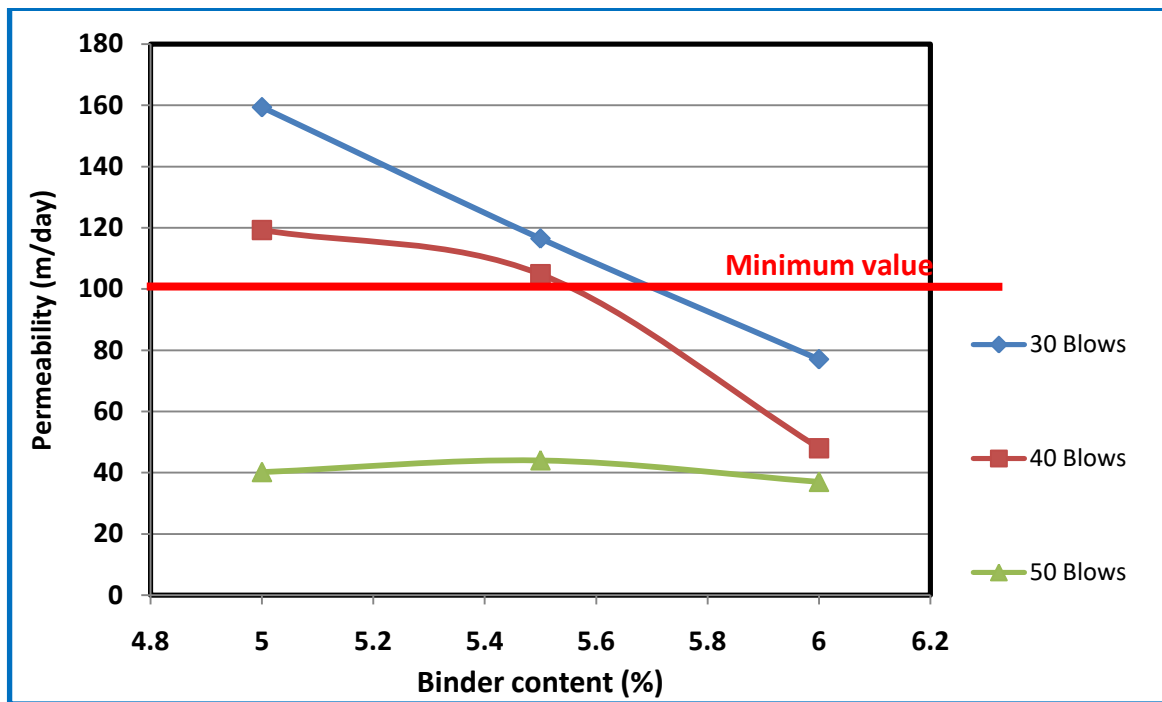


Figure 4. 5 : Binder Content V/S Permeability

4.9 INDIRECT TENSILE STRENGTH RESULT (IDT)

Indirect tensile strength was calculated at 5%, 5.5% and 6% bitumen content by weight of aggregates, at 30, 40, 50 blows of hammers on dry and wet conditioned samples. ITS values on dry tests show that ITS value increases with increase in number of blows. The same pattern is also observed on wet samples and wet samples also show that ITS value increases with increase in bitumen content. ITS values on dry and wet samples are shown in Table 4.19 and Table 4.20 respectively.

Table 4. 19 : Indirect Tensile Strength (ITS) Result on Dry Condition

Sample ID	Bitumen content	Number of blows	average diameter of sample (D)	average height of sample (t)	Load	Factor	Load	IDT (S1) = $(2000 \cdot P) / (\pi \cdot t \cdot D)$
	%		Mm	mm	Kgf		N	Kpa
2	5	30	101.3	76	50	7.1	3479	287.83
4		40	100	75.2	62	7.1	4314	365.39
7		50	101	73.6	66	7.1	4592.3	393.49
11	5.5	30	100	77.8	50	7.1	3479	284.82
16		40	100.6	76.6	55	7.1	3826.9	316.32
14		50	101.6	75.2	51	7.1	3548.6	295.83
20	6	30	99.9	78	50	7.1	3479	284.38
22		40	100	76.9	60	7.1	4174.8	345.79
25		50	101.2	75.5	65	7.1	4522.7	377.03

Table 4. 20 : Indirect Tensile Strength (ITS) Result on Wet Condition

Sample ID	Bitumen content	Number of blows	Average diameter of sample (D)	Average height of sample (t)	Load	Load	IDT (S2) = $(2000*P)/(\pi*t*D)$
	%		mm	mm	Kgf	N	Kpa
37	5	30	101.1	75.8	0	1942	161.41
38		40	100.5	74	276	2704.8	231.65
39		50	101	73.2	363	3557.4	306.48
40	5.5	30	100.5	77.8	306	2742	223.37
41		40	100.3	76.3	309	3044	253.35
42		50	100	76	431	3250	272.38
43	6	30	100.4	77.9	289	2832.2	230.65
44		40	100.2	77.1	377	3694.6	304.61
45		50	100.6	75.8	388	3802.4	317.61

4.10 MOISTURE SUSCEPTIBILITY TEST RESULT

Moisture susceptibility was calculated as the ratio of wet ITS value to the dry ITS value. Minimum recommended moisture susceptibility value is 80%. The values calculated for moisture susceptibility is represented in Table 4.21 and Figure 4.6. The test values at 5% bitumen content by weight of aggregates are less than 80%, at 5.5% only 40 and 50 blows sample satisfied the criteria of 80% and at 6% all samples satisfied the minimum 80% criteria. The test value shows that moisture susceptibility increases with increase in number of blows and increase in bitumen content. With increase in number of blows air void content decreases, air void content decreases contact surface area with water also decreases and it increases the moisture susceptibility.

Table 4. 21 : Moisture Induced Susceptibility Test Result

Bitumen content	Number of blows	IDT (S1) = (2000*P)/(Π*t*D)	IDT (S2) = (2000*P)/(Π*t*D)	S2/S1
%		Kpa	Kpa	%
5	30	287.83	161.41	56.08
	40	365.39	231.65	63.40
	50	393.49	306.48	77.89
5.5	30	284.82	223.37	78.42
	40	316.32	253.35	80.09
	50	295.83	272.38	92.07
6	30	284.38	230.65	81.11
	40	345.79	304.61	88.09
	50	377.03	317.61	84.24

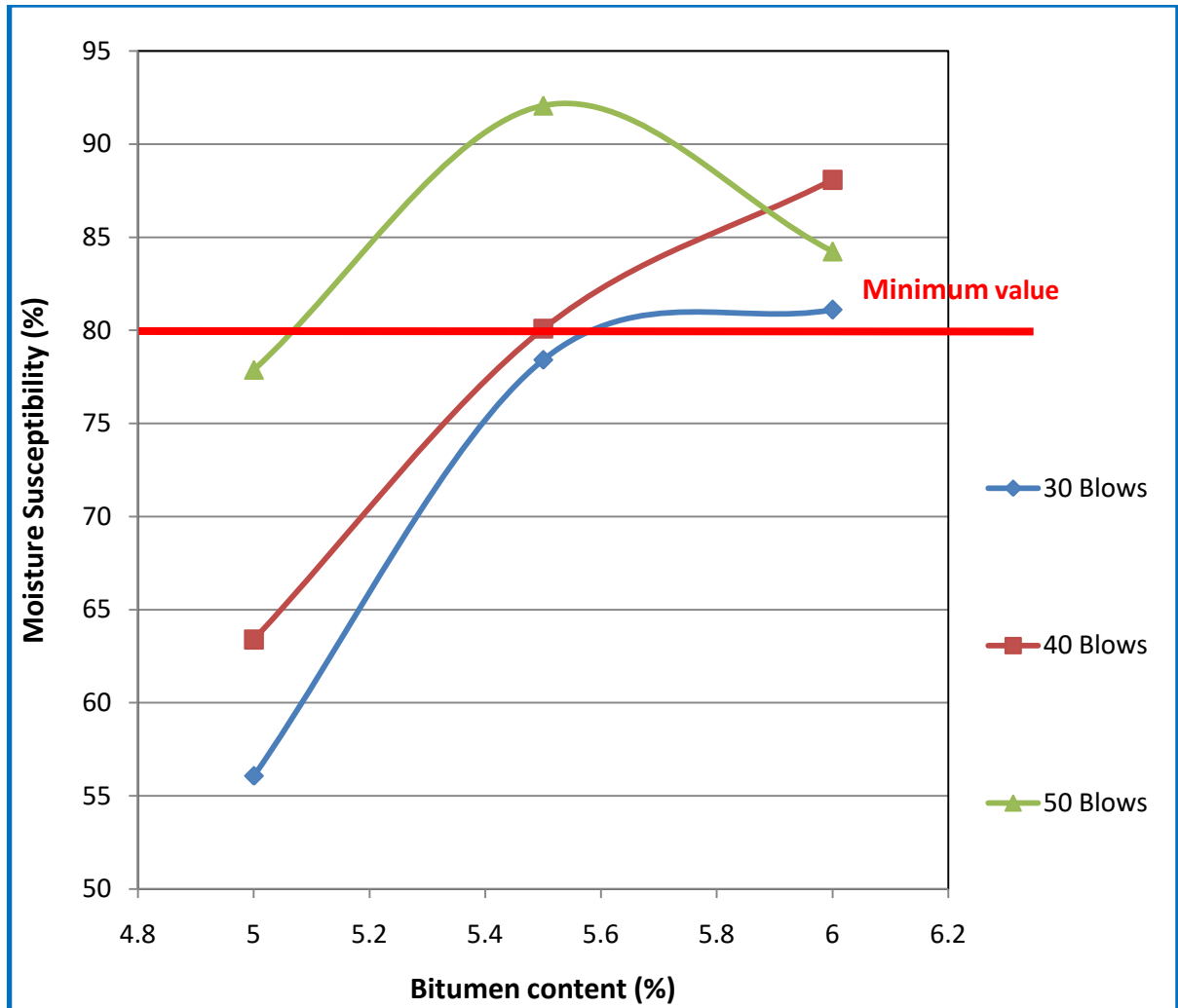


Figure 4. 6 : Bitumen Content Versus Moisture Susceptibility

4.11 SKID RESISTANCE TEST RESULT

BPT was used to find out skid resistance number. Higher the skid resistance number better will be the road condition. Table 4.22 and Figure 4.7 shows the result obtained from British pendulum tester. Two pavements were compared; permeable asphalt pavement gave better result in both dry and wet condition as compared to dense asphalt pavement.

Table 4. 22 : Skid Resistance of Permeable Asphalt Pavement and Dense Asphalt Pavement on Dry and Wet Condition

S. No.	Dry Condition (British Pendulum Number)	Average Value	Wet Condition (British Pendulum Number)	Average Value
Dense Asphlat Pavement	75	71.67	65	65
	70		65	
	70		65	
Porous Asphlat Pavement	100	100	75	75
	100		75	
	100		75	

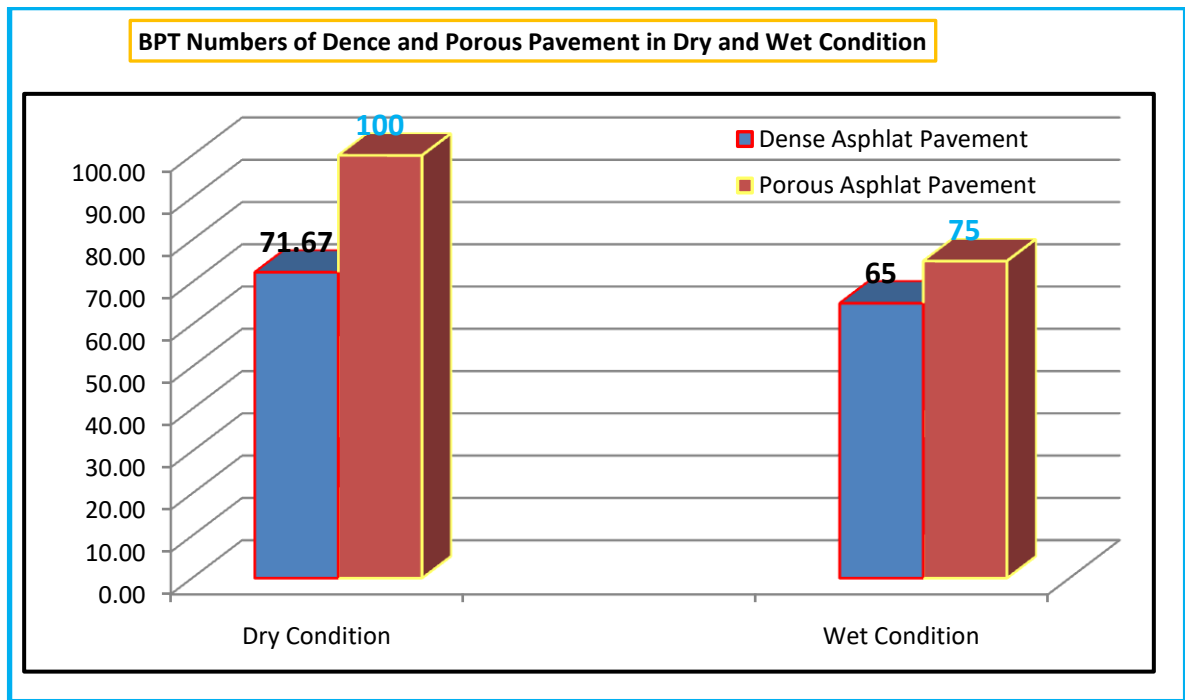


Figure 4. 7 : Skid Resistance of Permeable Asphalt Pavement and Dense Asphalt Pavement on Dry and Wet Condition

4.12 DYNAMIC CREEP TEST RESULT

Dynamic creep test shows the rutting potential. At 5% bitumen content by weight of aggregates, result shows that total permanent strain was decreasing with increase in number of blows at same bitumen content. Table 4.23 and Figure 4.8 also shows that with increase in number of blows at same bitumen content total permanent strain decreases and also with increases in bitumen content total permanent strain decreases.

Table 4. 23 : Dynamic Creep Test Result

Bitumen content	Number of blows	Cycle	Total permanent strain
%			%
5	30	403	1.3
	40	588	0.986
	50	1800	1.201
5.5	30	599	3.034
	40	467	2.89
	50	1321	2.48
6	30	108	1.8
	40	594	1.5
	50	637	1.2

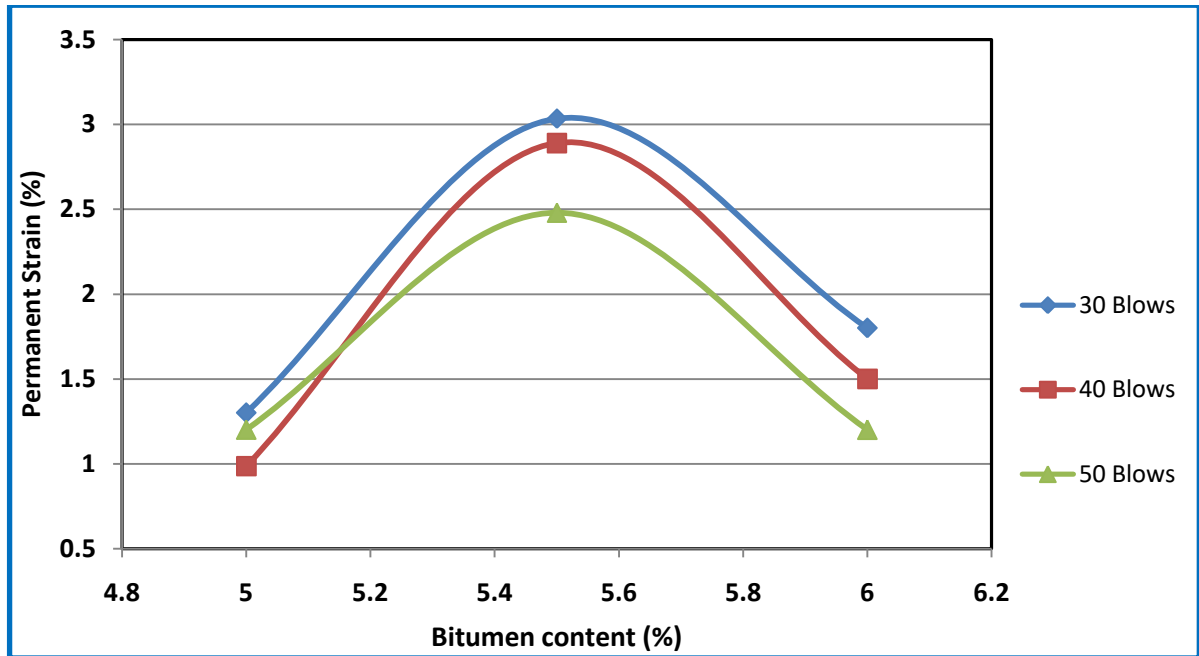


Figure 4. 8 : Bitumen Content versus Permanent Strain

4.13 FILTER LAYER

4.13.1 Filter layer VCA_{DRC}

Filter layer was designed with air void content between surface layer and reservoir course so that material of surface layer do not pass into the reservoir layer and also it provides a stabilize bed surface for the surface course. Minimum void content for surface and reservoir layer is 18% and 40%.

Void in coarse aggregate at dry rodded condition was obtained and table 4.24 shows the result. Air void content obtained in filter course is 37.30, this satisfied the above condition.

Table 4. 24 : Filter Layer VCA (Dry Rodded Condition)

Layer	Weight of compacted aggregate	Volume of mould	Bulk density of aggregates	Theoretical sp. Gr. of dry aggregates	Dry aggregate air voids (VCA)
	Kg	L	Kg/m³		%
Choker course	21.57	13.79	1564.41	2.50	37.30

4.14 RESERVOIR LAYER

4.14.1 Reservoir layer VCA_{DRC}

For the design of reservoir layer minimum air void content should be 40%. This layer was designed for storing water temporary period of time. Air void content obtained from dry rodded condition is 44.43% which is more than specified value.VCA is shown in Table 4.25.

Table 4. 25 : Reservoir Layer VCA (Dry Rodded Condition)

Layer	Weight of compacted aggregate	Volume of mould	Bulk density of aggregates	Theoretical sp. Gr. of dry aggregates	Dry aggregate air voids (VCA)
	Kg	L	Kg/m³		%
Reservoir course	19.34	13.79	1403.09	2.53	44.43

4.14.2 Reservoir Layer Hydraulic Design

Depth of reservoir layer was calculated according to the equation (4.3) given below by stormwater management guidebook, District of Columbia.

$$D_p = \left\{ \left(P * Rv * \frac{Da}{Ap} \right) - \left(i * \frac{tf}{2} \right) \right\} / n \quad (\text{Eq. 4.3})$$

Parameters used are:

D_p is the reservoir layer depth in feet

P is the rainfall depth = 214mm = 0.70 feet as per south Delhi data

R_v is the runoff coefficient for impervious area and taken as 0.95

D_a is the total drainage area, including porous road area (sf.), minimum taken as two times of porous road area

A_p is the porous road area (sf.)

i is the infiltration rate of subgrade soil = 0.20inch/hour = 0.39feet/day

(Consider as moderate infiltration rate)

t_f is the time to fill the layer (day), and suggested as 2 hours or 0.083 day

η is the effective porosity of layer and taken as 0.31

All the values are put into formula provided above and depth of reservoir layer obtained is given below.

Depth of reservoir layer = 4.32 feet

Permeable Pavement Storage Volume was calculated by equation (4.5).

$$S_V = (D_p * \eta * A_p) + (i * t_f / 2) \quad (\text{Eq. 4.5})$$

Parameters used are:

D_p is the reservoir layer depth = 4.32 feet

η is the effective porosity for the reservoir layer = 0.31

A_p is the porous road area = 9 ft²

i is the infiltration rate of subgrade soil = 0.20inch/hour = 0.39feet/day

tf is the time to fill the layer (day), and suggested as 2 hours or 0.083 day

Storage volume was obtained as 11.87 (ft³)

Table 4.26 shows parameter adopted for hydraulic design

Table 4. 26 : Prameters Adopted in Hydraulic Design

P	Rainfall depth	ft	0.70
Rv	Runoff coefficient of impervious area		0.95
DA	Total drainage area	ft ²	18.00
Ap	Permeable pavement surface area	ft ²	9.00
i	Permeability of subgrade soil	ft/day	0.39
tf	Time for filling the reservoir course	day	0.08
n	Effective porosity of reservoir course		0.31
Dp	Reservoir course depth	ft	4.32
Sv	Storage volume	ft ³	11.87
di	Depth of underdrain above subgrade	ft	0.11
	Depth of reservoir above underdrain	ft	4.21

4.15 DEMONSTRATION OF PROTOTYPE

A prototype of porous asphalt pavement was also designed to analyze how porous asphalt pavement performs as shown in Figure 4.9 and Figure 4.10. The prototype was made up of fabric with width 2cm, outer dimension of prototype was, 59cm height, 40cm length and 29 cm width. Width 2cm from the bottom of the prototype at a height of 11cm a perforated fabric wall was provided to collect the water from the upper layers. Holes were also provided at the bottom to remove water from prototype.

A 20cm reservoir layer thickness was decided for the prototype with density of coarse aggregates 1403kg/m^3 .

Total material required for reservoir course = thickness of reservoir course * length of

$$\begin{aligned} & \text{Prototype * width of prototype} \\ & = 20 * 36 * 25 * 1.403 \\ & = 25200 \text{ kg.} \end{aligned}$$

A 10cm choker course thickness was decided for the prototype with density of coarse aggregates 1564kg/m^3 .

Material required for choker course = thickness of choker course * length of prototype *

$$\begin{aligned} & \text{Width of prototype} \\ & = 10 * 36 * 25 * 1.564 \\ & = 14076 \text{ kg} \end{aligned}$$

For surface layer, a slab was designed at optimum binder content 5.5% by weight of mix. Procedure for casting the slab was already explained in chapter 3. Thickness of slab was 5.29 cm with air void content 20% and permeability 110m/day.



Figure 4. 9 : Prototype for Porous Asphalt Pavement



Figure 4. 10 : Prototype Showing Layers in Porous Asphalt Pavement

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Porous bitumen pavement provides sustainable technology which reduces storm water management, control runoff from impervious area and safety for road users. Aggregates used in this project were easily available in local area (Delhi). Bitumen chosen for this project was VG30 and pellet fiber was also added to increase the performance of porous asphalt mix. Gradation for surface layer was chosen which satisfy the ASTM, UNHC, NCAT and NAPA gradation. Marshal mix design method was used for optimizing the binder and various samples required in the project. The mix design was carried out at three bitumen content 5 percent, 5.5 percent and 6 percent by weight of aggregates, with different number of marshal blows 30, 40 and 50 for optimization of result.

In optimizing the bitumen content, air void criteria of minimum 18 percent was satisfied at each bitumen content except at 5.5% bitumen content by weight of aggregates with 50 marshal blows and at 6% bitumen content by weight of aggregates with 40 and 50 marshal blows. Drain-down test was satisfied at each bitumen content. Cantabro test for dry sample was satisfied at each bitumen content but for wet samples only 5.5% and 6% bitumen content with 40 and 50 marshal blows satisfied the cantabro loss criteria. So based on three test result air void content, darin-down test and cantabro test it was concluded that optimum binder content is 5.5 percent with 40 blows of marshal hammer.

Minimum recommended permeability value for porous asphalt pavement is 100 m/day. Permeability value was satisfied at 5% and 5.5% bitumen content by weight of aggregates with 30 and 40 blows of marshal hammer and at 6% bitumen content only 30 blows of hammer satisfied the result.

Minimum moisture susceptibility value is 80 percent as per ASTM. Here it was concluded that moisture susceptibility was satisfied at 5.5% bitumen content by weight of aggregates with 40 and 50 blows of marshal hammer and at 6% bitumen content all the values were satisfied. Dynamic creep test shows decrease in trend of permanent strain with increase in number of blows.

Filter layer was designed with air void content 37.3 percent. Filter layer was designed as a layer which stabilizes the surface layer and prevent migration of surface particle to the reservoir layer.

Reservoir layer store water for short period of time with minimum air void content 40 percent. Here the air void provided in reservoir layer was 44.43 percent. Thickness of resevoir layer was adopted based on rainfall of 214mm (South Delhi data) 4.32 feet.

A prototype was also constructed for checking the permeability with thickness of surface layer 5.29cm, choker course 10cm and reservoir course 20cm.

Design methodology for surface layer, filter layer and reservoir layer can be used as guideline for porous asphalt pavement design.

5.2 RECOMMENDATION

This one year dissertation work focus on design of surface layer, choker layer and reservoir layer for porous asphalt pavement with marshal mix design method. In this study only the designing part is focused. The following recommendations for future research may be provided which will attract government and various agencies to use porous pavement.

Porous asphalt provides many advantageous applications which are very helpful for the society and from economic point of view. But still porous asphalt pavement need further research so that porous pavement can be used for the heavily trafficked roads.

Porous asphalt pavement has more air void content which gets clogged with time and affects the functioning of pavement. Porosity of pavement is mostly affected in sand blows area and in cold countries due to formation of ice.

Due to above factor life of porous asphalt pavement decreases as compare to dense pavement. So it is recommended that strength factor, clogging of voids and durability of porous asphalt pavement needs further research.

Porous asphalt pavement needs performance evaluation by laying a trial section to visualize and observe the various characteristics of road.

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